THE XYZs OF USING A SCOPE

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CONTENTS

INTRODUCTION

If you watch an electrical engineer tackling a tough design project, or a service engineer troubleshooting a stubborn problem, you'll see them grab a scope, fit probes or cables, and start turning knobs and setting switches without ever seeming to glance at the front panel. To these experienced users, the oscilloscope is their most important tool but their minds are focused on solving the problem, not on using the scope.

Making oscilloscope measurements is second nature to them. It can be for you too, but before you can duplicate the ease with which they use a scope, you will need to concentrate on learning about the scope itself: both how it works and how to make it work for you.

The purpose of this primer is to help you learn enough about oscilloscopes and oscilloscope measurements that you will be able to use these measurement tools quickly, easily, and accurately.

The text is divided into two parts:

The first four chapters of Part I describe the functional parts of scopes and the controls associated with those parts. Then a chapter on probes concludes the section.

Part II allows you to build on the knowledge and experience you gained from Part I. The signals you'll see on the screen of an oscilloscope are identified by waveshape and the terms for parts of waveforms are discussed. The next two chapters cover safety topics and instrument set-up procedures.

Then Chapter 9 describes measurement techniques. Exercises there let you practice some basic measurements, and several examples of advanced techniques that can help you make more accurate and convenient measurements are also included. The last chapter in this primer discusses oscilloscope performance and its effects on your measurements.

Having a scope in front of you while working through the chapters is the best way to both learn and practice applying your new knowledge. While the fundamentals will apply to almost any scope, the exercises and illustrations use two specific instruments: the Tektronix 2213 and 2215 Portable Oscilloscopes. The 2213 is a dual-channel, 60 MHz portable designed as an easy-to-use, lightweight, general-purpose oscilloscope. The 2215 is a dual time base oscilloscope with more features and capabilities; it's included so you will understand dual time base scopes and appreciate the additional measurement capabilities they offer.

If you have comments or questions about the material in this primer, please don't hesitate to write.

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PART I. SCOPES, CONTROLS, & PROBES

You can measure almost anything with the two-dimensional graph drawn by an oscilloscope. In most applications the scope shows you a graph of voltage (on the vertical axis) versus time (on the horizontal axis). This general-purpose display presents far more information than is available from other test and measurement instruments like frequency counters or multimeters. For example, with a scope you can find out how much of a signal is direct, how much is alternating, how much is noise (and whether or not the noise is changing with time), and what the frequency of the signal is as well. Using a scope lets you see everything at once rather than requiring you to make many separate tests.

Most electrical signals can be easily connected to the scope with either probes or cables. And then for measuring nonelectrical phenomena, transducers are available. Transducers change one kind of energy into another. Speakers and microphones are two examples; the first changes electrical energy to sound waves and the second converts sound into electricity. Other typical transducers can transform mechanical stress, pressure, light, or heat into electrical signals. You can see that given the proper transducer, your test and measurement capabilities are almost endless with an oscilloscope.

Making measurements is easier if you understand the basics of how a scope works. You can think of the instrument in terms of the functional blocks illustrated in Figure 1: *vertical system, trigger system, horizontal system,* and *display system.*

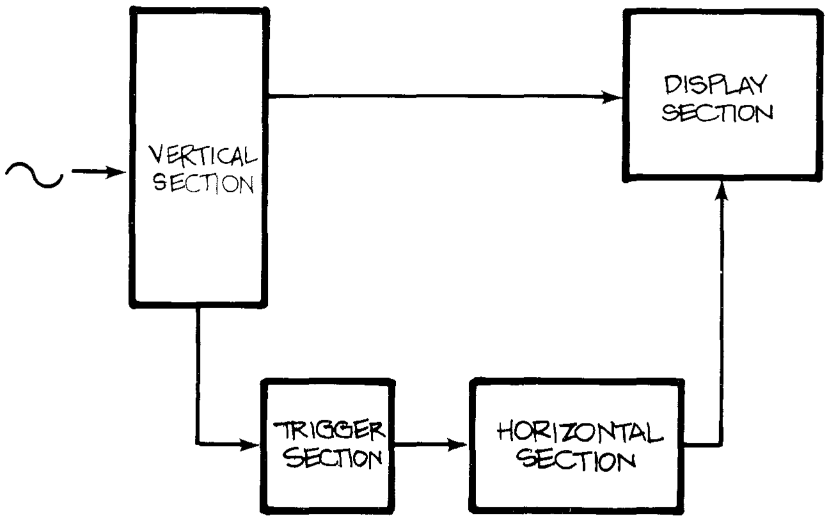


Figure 1.
THE BASIC OSCILLOSCOPE in its most general form has only four functional blocks: vertical, horizontal, trigger, and display systems (and sometimes, sections). The display system is also sometimes called the *CRT* (for cathode-ray tube) *section.*

Each is named for its function. The vertical system controls the vertical axis of the graph; anytime the electron beam that draws the graph moves up or down, it does so under control of the vertical system. The horizontal system controls the left to right movement of the beam. The trigger system determines when the oscilloscope draws; it *triggers* the beginning of the horizontal sweep across the screen. And the display system contains the cathode-ray tube, where the graph is drawn.

This part of the primer is divided into chapters for each of those functional blocks. The controls for each block are named first, and you can use a two-page, fold-out illustration of a Tektronix 2213 front panel at the back of the primer to locate them on your scope. Next the controls and their functions are described, and at the end of each chapter there are hands-on exercises using those controls.

The last chapter in this section describes probes. When you finish reading these five chapters, you'll be ready to make fast and accurate oscilloscope measurements.

But before you turn on your scope, remember that you should always be careful when you work with electrical equipment. Observe *all* safety precautions in your test and measurement operations. Always plug the power cord of the scope into a properly-wired receptacle before connecting your probes or turning on the scope; use the proper power cord for your scope, and use only the correct fuse. Don't remove the covers and panels of your scope.

Now fold out the front panel illustration at the back of the primer, so that it is visible as you read. Use the foldout and follow Exercise 1 to *initialize* (set in standard positions) the scope controls. These standard settings are necessary so that as you follow the directions on these pages, you'll see the same thing on your scope's CRT as is pictured or described here.

Exercise 1. INITIALIZING THE SCOPE

Use the foldout figure and callouts to locate the controls mentioned here.

1. *DISPLAY SYSTEM CONTROLS: Set the AUTO INTENSITY control at midrange (about halfway from either stop). Turn the AUTO FOCUS knob completely clockwise.*

2. *VERTICAL SYSTEM CONTROLS: Turn the channel 1 POSITION control completely counterclockwise. Make sure the lefthand VERTICAL MODE switch is set to CH 1. Move both channel VOLTS/DIV switches to the least sensitive setting by rotating them completely counterclockwise. And make sure the center, red CAL controls are locked in their detents at the extreme clockwise position. Input coupling switches should be set to GND.*

3. *HORIZONTAL SYSTEM CONTROLS: Make sure the HORIZONTAL MODE switch is set to NO DLY for no delay. (If you're using a 2215, move the switch to the A sweep position.) Rotate the SEC/DIV switch to 0.5 millisecond (0.5 ms). Make sure the red CAL (variable) switch in the center of the knob is in its detent position by moving it completely clockwise. And push in on the CAL switch to make sure the scope is not in a magnified mode.*

4. *TRIGGER SYSTEM CONTROLS: Make sure the CAL HOLDOFF control is set to its full counterclockwise position. Set the trigger MODE switch (2215: A TRIGGER MODE) on AUTO. And move the trigger SOURCE switch (A SOURCE on a 2215) to INT (internal) and the INT selection switch (A&B INT on a 2215) to CH 1.*

After following the steps in Exercise 1, you should plug your scope into a properly-grounded outlet and turn it on. With a Tektronix 2200 scope, there's no need to change the scope's power supply settings to match the local power line; the scopes operate on main power from 90 to 250 Vac at 48 to 62 Hz.

CHAPTER 1. THE DISPLAY SYSTEM

The oscilloscope draws a graph by moving an electron beam across a phosphor coating on the inside of the CRT (cathode-ray tube). The result is a glow for a short time afterward tracing the path of the beam. A grid of lines etched on the inside of the faceplate serves as the reference for your measurements; this is the *graticule* shown in Figure 2.

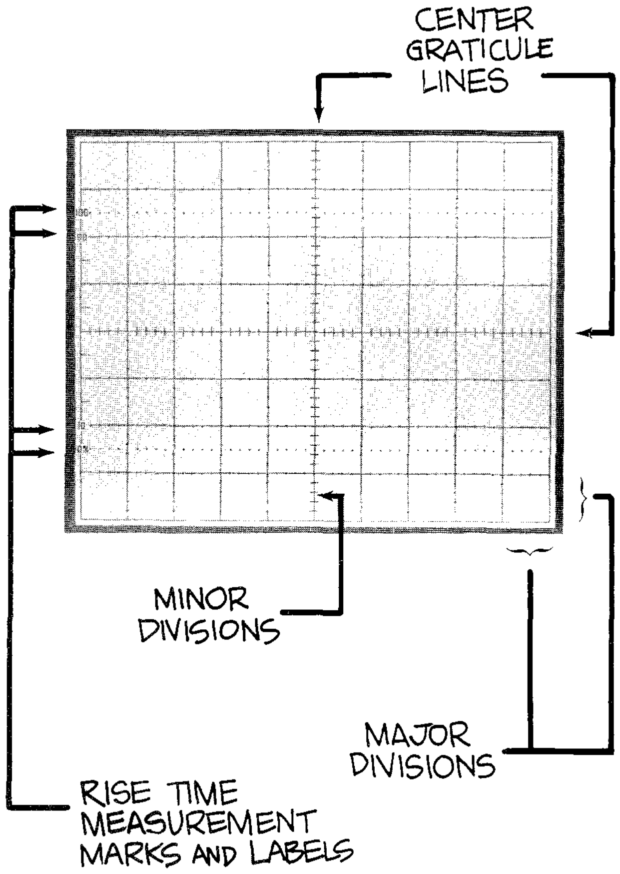


Figure 2.
THE GRATICULE is a grid of lines typically etched or silk-screened on the inside of the CRT faceplate. Putting the graticule inside — on the same plane as the trace drawn by the electron beam, and not on the outside of the glass — eliminates measurement inaccuracies called *parallax errors*. Parallax errors occur when the trace and the graticule are on different planes and the observer is shifted slightly from the direct line of sight. Though different sized CRT's may be used, graticules are usually laid out in an 8 x 10 pattern. Each of the eight vertical and ten horizontal lines block off *major divisions* (or just *divisions*) of the screen. The labeling on scope controls always refers to major divisions. The tick marks on the center graticule lines represent *minor divisions* or *subdivisions*. Since rise time measurements are very common, 2200 Series scope graticules include rise time measurement markings: dashed lines for 0 and 100% points, and labeled graticule lines for 10 and 90%

Common controls for display systems include intensity and focus; less often, you will also find beam finder and trace rotation controls. On a Tektronix 2200 Series instrument they are all present, grouped next to and on the right of the CRT. At the top of the group is the intensity control (labeled AUTO INTENSITY on a 2200 because these instruments automatically maintain the trace intensity once it is set). The TRACE ROTATION adjustment is under that, and then the beam finder (BEAM FIND). Under the probe adjustment jack is the focus control (labeled AUTO FOCUS because it's also automatic). The functions of these controls are described below and their positions on the Tektronix 2213 Portable Oscilloscope are illustrated by the foldout illustration at the rear of the booklet.

Beam Finder

The beam finder is a convenience control that allows you to locate the electron beam anytime it's off-screen. When you push the BEAM FIND button, you reduce the vertical and horizontal deflection voltages (more about deflection voltages later) and over-ride the intensity control so that the beam always appears within the 8 x 10-centimeter screen. When you see which quadrant of the screen the beam appears in, you'll know which directions to turn the horizontal and vertical POSITION controls to reposition the trace on the screen for normal operations.

Intensity

An intensity control adjusts the brightness of the trace. It's necessary because you use a scope in different ambient light conditions and with many kinds of signals. For instance, on square waves you might want to change the trace brightness to look at different parts of the waveform because the slower horizontal components will always appear brighter than the faster vertical components.

Intensity controls are also useful because the intensity of a trace is a function of both how bright the beam is and how long it's on-screen. As you select different sweep speeds (a *sweep* is one movement of the electron beam across the scope screen) with the SEC/DIV switch, the beam ON and OFF times change and the beam has more or less time to excite the phosphor.

On most scopes, you have to turn the intensity up or down to restore the initial brightness. On the 2200 Series scopes, however, the automatic intensity circuit compensates for changes in sweep speed from 0.5 milliseconds (0.5 ms) to 0.5 microseconds (0.5 μs). Within this range, the automatic circuit maintains the same trace intensity you initially set with the AUTO INTENSITY control.

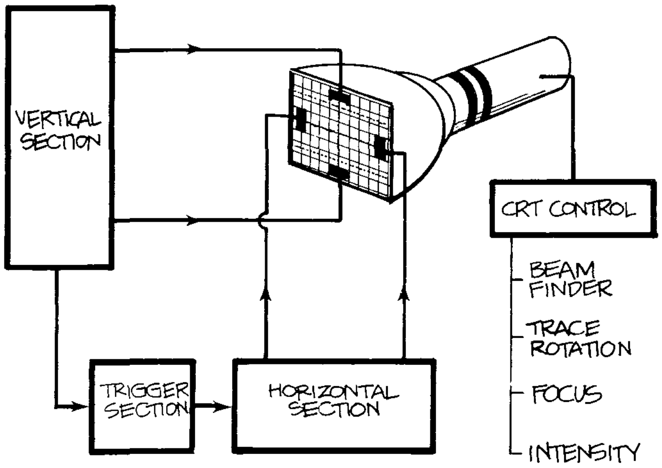
Focus

The scope's electron beam is focused on the CRT faceplate by an electrical grid within the tube. The focus control adjusts that grid for optimum trace focus. On a 2200 scope, the AUTO FOCUS circuit maintains your focus settings over most intensity settings (0.5 ms to 0.5 μs).

Trace Rotation
Another display control you'll find on the front panel of a 2200 Series instrument is TRACE ROTATION. The trace rotation adjustment allows you to electrically align the horizontal deflection of the trace with the fixed graticule. To avoid accidental misalignments when the scope is in use, the control is recessed and must be adjusted with a small screwdriver.

If this seems like a calibration item that should be adjusted once and then forgotten, you're right; that's true for most oscilloscope applications. But the earth's magnetic field affects the trace alignment and when a scope is used in many different positions — as a service scope will be — it's very handy to have a front panel trace rotation adjustment.

Using the Display Controls
The display system and its controls are shown as functional blocks in Figure 3. Use Exercise 2 to review the display controls.



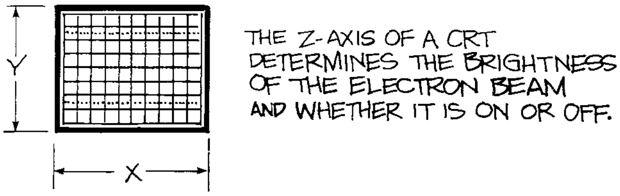


Figure 3.
THE DISPLAY SYSTEM of your scope consists of the cathode-ray tube and its controls. To draw the graph of your measurements, the vertical system of the scope supplies the Y, or vertical, coordinates and the horizontal system supplies the X coordinates. There is also a Z dimension in a scope; it determines whether or not the electron beam is turned on, and how bright it is when it's on.

Exercise 2. THE DISPLAY SYSTEM CONTROLS

In Exercise 1 you initialized your scope and turned on the power. Now you can find the display system controls labeled on the foldout front panel illustration and use them as you follow these instructions.

1. *BEAM FIND: Locate the position of the electron beam by pushing and holding in the BEAM FIND button; then use the channel 1 vertical POSITION knob to position the trace on the center horizontal graticule line. Keep BEAM FIND depressed and use the horizontal POSITION control to center the trace. Release the beam finder.*

2. *AUTO FOCUS: The trace you have on the screen now should be out of focus. Make it as sharp as possible with the AUTO FOCUS control.*

3. *AUTO INTENSITY: Set the brightness at a level you like.*

4. *Vertical POSITION: Now you can use the vertical POSITION control to line up the trace with the first major division line above the center of the graticule.*

5. *TRACE ROTATION: Use a small screwdriver and the TRACE ROTATION control to rotate the trace in both directions. When you finish, align the trace parallel to the horizontal division line closest to it. (After setting the trace rotation, you may have to use the vertical POSITION control again to align the trace on the graticule line.)*

You have used all the scope's display system controls. If at the end of one of these chapters you're not going to go on immediately, be sure to turn your scope off.

CHAPTER 2. THE VERTICAL SYSTEM

The vertical system of your scope supplies the display system with the Y axis — or vertical — information for the graph on the CRT screen. To do this, the vertical system takes the input signals and develops *deflection voltages.* The display system then uses the deflection voltages to control — deflect — the electron beam.

The vertical system also gives you a choice of how you connect the input signals (called *coupling* and described below). And the vertical system provides internal signals for the trigger circuit (described in Chapter 4). Figure 4 illustrates the vertical system schematically.

Some of the vertical system controls — see the foldout front panel illustration for their locations — are: vertical position, sensitivity, and input coupling.

Because all 2200s are two-channel scopes, you will have one set of these switches for each channel. There are also two switches for choosing the scope's vertical display mode and one control that allows you to invert the polarity of the channel 2 signal.

For the exercises in this chapter, you'll need a 10X probe like the Tektronix P6120 10X Probes supplied with every 2200 Series scope.

Vertical Position

Your scope's POSITION controls let you place the trace exactly where you want it on the screen. The two vertical POSITION controls (there's one for each channel) change the vertical placement of the traces from each vertical channel; the horizontal POSITION control changes the horizontal position of both channels at once.

Input Coupling

The input coupling switch for each vertical channel lets you control how the input signal is *coupled* to the vertical channel. DC (the abbreviation normally stands for *direct current)* input coupling lets you see all of an input signal. AC *(alternating current)* coupling blocks the constant signal components and permits only the alternating components of the input signal to reach the channel. An illustration of the differences is shown in Figure 5.

The middle position of the coupling switches is marked GND for ground. Choosing this position disconnects the input signal from the vertical system and makes a triggered display show the scope's chassis ground. The position of the trace on the screen in this mode is the ground reference level. Switching from AC or DC to GND and back is a handy way to measure signal voltage levels with respect to chassis ground. (Using the GND position does not ground the signal in the circuit you're probing.)

Vertical Sensitivity

A volts/division rotary switch controls the sensitivity of each vertical channel. Having different sensitivities extends the range of the scope's applications; with a VOLTS/DIV switch, a multipurpose scope is capable of accurately displaying signal levels from millivolts to many volts.

Using the volts/division switch to change sensitivity also changes the *scale factor,* the value of each major division on the screen. Each setting of the control knob is marked with a number that represents the scale factor for that channel. For example, with a setting of 10 V,

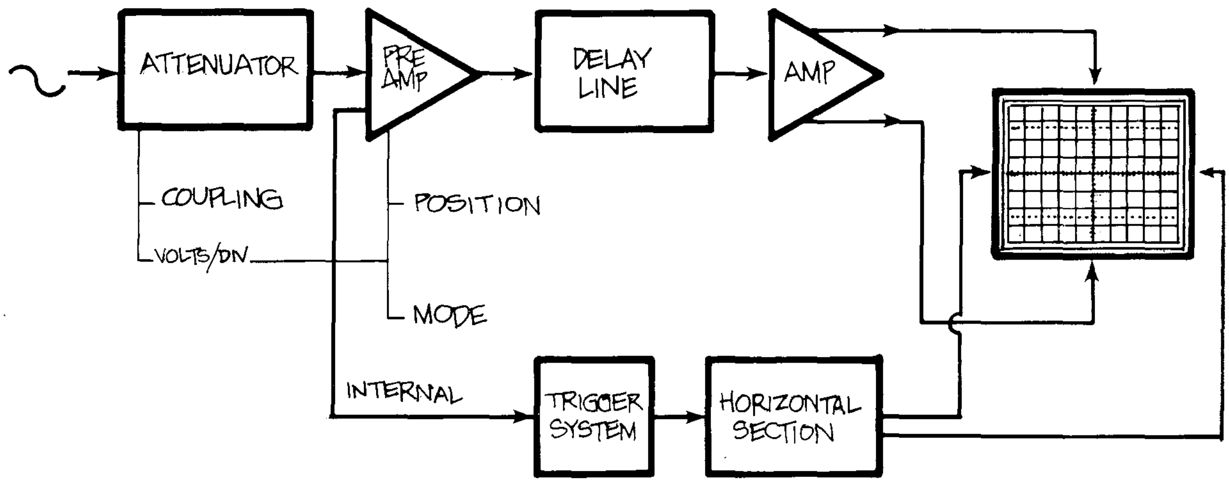


Figure 4.
THE VERTICAL SYSTEM of a Tektronix 2200 Series scope consists of two identical channels though only one is shown in the drawing. Each channel has circuits to couple an input signal to that channel, attenuate (reduce) the input signal when necessary, preamplify it, delay it, and finally amplify the signal for use by the display system. The delay line lets you see the beginning of a waveform even when the scope is triggering on it.

each of the eight vertical major divisions represents 10 volts and the entire screen can show 80 volts from bottom to top. With a VOLTS/DIV setting of 2 millivolts, the screen can display 16 mV from top to bottom.

If you pronounce the "/" in VOLTS/DIV as "per" when you read the setting, then you'll remember the setting is a scale factor; for example, read a 20 mV setting as "20 millivolts per division."

The probe you use influences the scale factor. Note that there are two unshaded areas under the skirts of the VOLTS/DIV switches. The right-hand area shows the scale factor when you use the standard 10X probe. The left area shows the factor for a 1X probe.

Variable VOLTS/DIV
The red CAL control in the center of the VOLTS/DIV switch provides a continuously variable change in the scale factor to a maximum greater than 2.5 times the VOLTS/DIV setting.

A variable sensitivity control is useful when you want to make quick amplitude comparisons on a series of signals. You could, for example, take a known signal of almost any amplitude and use the CAL control to make sure the waveform fits exactly on major division graticule lines. Then as you used the same vertical channel to look at other signals, you could quickly see whether or not the later signals had the same amplitude.

Channel 2 Inversion
To make differential measurements (described in Part II), you have to invert the polarity of one of your input channels. The INVERT control on the vertical amplifier for channel 2 provides this facility. When you push it in, the signal on channel 2 is inverted. When the switch is out, both channels have the same polarity.

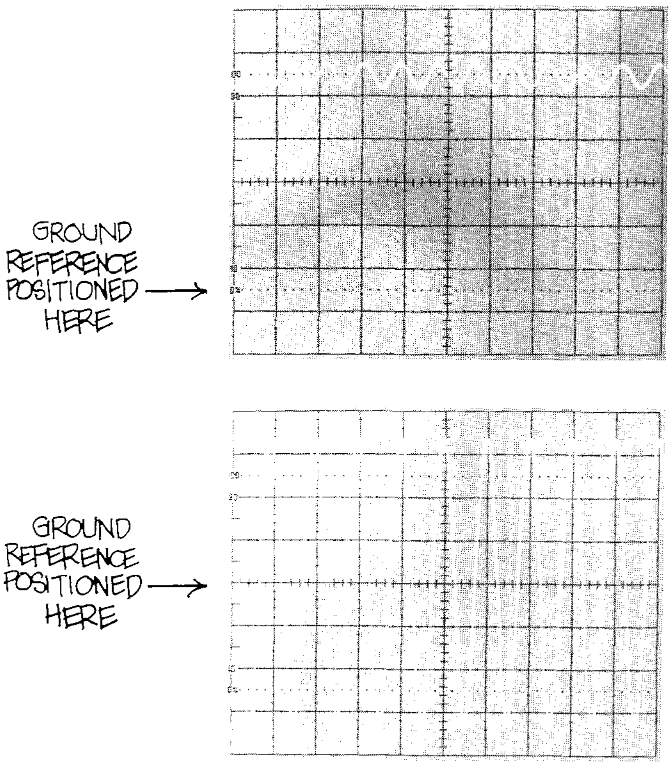


Figure 5.
VERTICAL CHANNEL INPUT COUPLING CONTROLS let you choose AC and DC input coupling and ground. DC coupling connects the entire input signal to the vertical channel. AC coupling blocks constant signal components and only connects alternating components to the vertical channel. The GND position disconnects the input signal and shows you the scope's chassis ground level. AC coupling is handy when the entire signal (alternating plus constant components) might be too large for the VOLTS/DIV switch settings you want. In a case like this, you might see something like the first photo. But eliminating the direct component allows you to look at the alternating signal with a VOLTS/DIV setting that is more convenient as in the second photo.

Vertical Operating Modes
Scopes are more useful if they have more than one vertical display mode, and with your Tektronix 2200, you have several controlled by two VERTICAL MODE switches: channel 1 alone; channel 2 alone; both channels in either the alternate or chopped mode; and both channels algebraically summed.

To make the scope display only channel 1, use the CH 1 position on the left-hand switch.

To display only channel 2, use the CH 2 position on the left-hand switch.

To see both channels in the alternate vertical mode, move the left-hand switch to BOTH (which enables the right-hand switch) and then move the right-hand switch to ALT. Now you can see both channels since the signals are drawn alternately. The scope completes a sweep on channel 1, then a sweep on channel 2, and so on.

To display both channels in the chop mode, you move the left-hand switch to BOTH and the right-hand one to CHOP. In the chop mode, the scope draws small parts of both signals by switching back and forth at a fast fixed rate while your eyes fill in the gaps.

THE VERTICAL SYSTEM CONT.

Both chop and alternate are provided so that you can look at two signals at any sweep speed. The alternate mode draws first one trace and then the other, but not both at the same time. This works great at the faster sweep speeds when your eyes can't see the alternating. To see two signals at the slower sweeps, you need the chop mode.

If you want to see the two input signals combined into one waveform on the screen, use BOTH on the left-hand and ADD on the right-hand switch. This gives you an algebraically-combined signal: either channel 1 and 2 added, (CH 1) + (CH 2); or channel 1 minus channel 2 when channel 2 is inverted, (+CH 1) + (−CH 2).

Alternate Sweep Separation
On the 2215 dual time base scope, there is also a sweep separation control: A/B SWP SEP. It's used to change the position of the scope's B sweep traces with respect to the A sweeps. Using the A/B sweep separation in conjunction with the vertical POSITION controls lets you place all four traces (two channels and two time bases) on the screen so that they don't overlap. (Dual time base scope measurements are described in Chapter 9.)

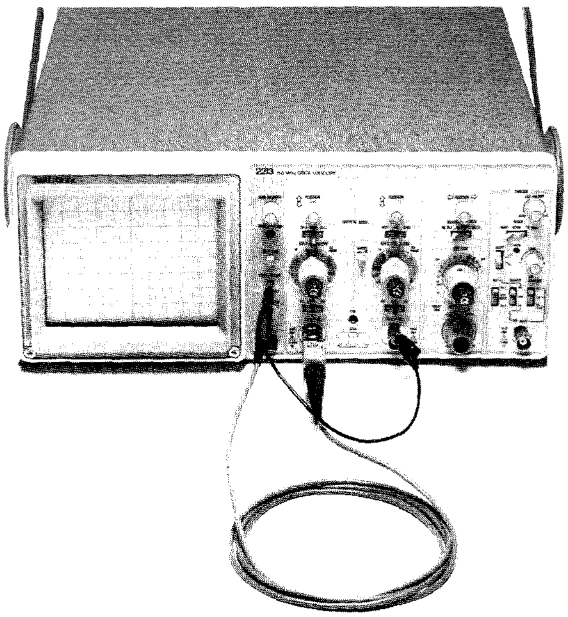


Figure 6.
THE TEKTRONIX P6120 10X PROBE connects to the BNC connector of either channel 1 (shown) or 2; unlike the photo, the probe's ground strap is usually connected to the ground of the circuit you are working on. The probe adjustment jack is labeled PROBE ADJUST and is located near the CRT controls on the front panel.

Using the Vertical Controls
Before using the vertical system controls, make sure all the controls are positioned where you left them at the end of the last chapter:

- AUTO INTENSITY and AUTO FOCUS set for a bright, crisp trace;
- trigger SOURCE (A SOURCE on the 2215) switch on INT and the INT (2215: A&B INT) switch on CH 1;
- trigger MODE (2215: A TRIGGER MODE) switch on AUTO;
- trigger VAR HOLDOFF control in its extreme counterclockwise position;
- SEC/DIV (2215: A and B SEC/DIV) switch to 0.5 ms;
- both channel VOLTS/DIV switches on 100 V (10X probe reading);
- both CAL VOLTS/DIV switches in their detents at the extreme clockwise position;
- input coupling levers in GND;
- VERTICAL MODE is CH 1;
- and HORIZONTAL MODE is NO DLY (2215 mode is A).

Now connect your 10X probe on the channel 1 BNC connector on the front panel of your scope. (BNC means "bayonet Neill-Concelman"; named for Paul Neill, who developed the N Series connector at Bell Labs, and Carl Concelman, who developed the C Series connector.)

Put the tip of the probe into the PROBE ADJ jack. Probes come with an alligator-clip ground strap that's used to ground the probe to the circuit-under-test. Clip the ground lead onto the collar of the channel 2 BNC connector as shown in Figure 6.

Use the callouts on the foldout figure to remind yourself of the control locations and follow the directions in Exercises 3 to review the vertical system controls.

Exercise 3. VERTICAL SYSTEM CONTROLS

Compensating Your Probe

1. *Turn on the scope and move the CH 1 VOLTS/DIV switch clockwise to 0.5 V; remember the P6120 is a 10X probe, so use the VOLTS/DIV readout to the right.*

2. *Switch the channel 1 input coupling to AC.*

3. *If the signal on the screen isn't steady, turn the trigger LEVEL (A TRIGGER LEVEL on the 2215) control until the signal stops moving and the TRIG'D light is on. (Use the AUTO FOCUS control if you think you can get the signal sharper, and AUTO INTENSITY to adjust the brightness.)*

4. *Next, compensate your probe. There's a screwdriver adjustment on the compensation box at the base of the probe; turn it until the tops and bottoms of the square wave on the screen are flat. (There's more information about probes and compensation in Chapter 5.)*

Controlling Vertical Sensitivity

1. *The probe adjustment signal is a square wave of approximately 0.5 volts, and the scale factor for channel 1 is now a half-volt per division. At this setting every major division on the screen represents half a volt. Use the channel 1 vertical POSITION control to line up the bottom edge of the waveform with the center graticule line. The tops of the square wave should be just touching the next major division line, proving the probe adjustment signal is approximately 0.5 volts. (Note that the probe adjustment signal is not a critical circuit in the scope; this is why the square wave is approximately 0.5 volts.)*

2. *Turn the VOLTS/DIV switch two more click stops to the right. The channel 1 scale factor is now 0.1 volts/division, and the signal – still half a volt – is now about five major divisions in amplitude.*

3. *Turn the CAL VOLTS/DIV control to the left. That will take it out of its calibrated detent position and let you see its effect. Since it reduces the scale factor ≥2½ times, the signal should be less than two major divisions in amplitude with this control all the way to the left. If it isn't exactly that, don't worry. The variable volts/division controls are used to compare signals, not make amplitude measurements, and consequently the exact range of variation isn't critical. Return the variable control to its detent.*

Coupling The Signal

1. *Switch your channel 1 input coupling to GND and position the trace on the center graticule. Switch back to the AC coupling position. Note that the waveform is centered on the screen. Move the CH 1 VOLTS/DIV switch back to 0.5 volts and note that the waveform is still centered around the zero reference line.*

2. *Switch to DC coupling. The top of the probe adjustment signal should be on the center graticule line and the signal should reach to the next lower major division. Now you can see the difference between AC and DC coupling. AC coupling blocked the constant part of the signal and just showed you a half-volt, peak-to-peak, square wave centered on the zero reference you set at the center of the screen. But the DC coupling showed you that the constant component of the square wave was all negative-going with respect to ground, because in DC, all signal components are connected to the vertical channel.*

The Vertical Mode Controls

1. *So far you've been using your scope to see what channel 1 can tell you, but that's only one of many possible vertical modes. Look at the trace for channel 2 by moving the scope's left-most VERTICAL MODE switch to CH 2. The input coupling for channel 2 should still be GND at this point, so what you'll see is the ground reference line. Line up this trace with the graticule line second from the top of the screen with the channel 2 POSITION control.*

2. *Now move the lever on the left-hand vertical mode switch to BOTH. That lets you pick one of the vertical modes controlled by the right-hand side vertical mode switch; move it to ALT. You've just selected the alternate vertical mode. In this mode, your scope alternates between the signals on channel 1 and 2, drawing one complete sweep on channel 1 first, and then drawing a complete sweep on channel 2. You can see this happening when you slow down the sweep speed, so move the SEC/DIV swtich left to 0.1 seconds per division. Now you can see the two dots from the AC-coupled channel 1 move across the screen for one sweep. Then the single dot from channel 2 will move across the screen. The point is that in the alternate mode each channel is drawn completely before the scope switches to the other channel.*

3. *Turn the SEC/DIV switch back to 0.5 ms and switch to CHOP as your vertical mode. The display looks a lot like the alternate mode, but the way it's achieved is entirely different. In alternate, you saw that one channel's signal was completely written before the other started. When you're looking at slow signals with your scope, that can be a bother because only one trace at a time will be on-screen. In the chop mode, however, the scope switches back and forth very quickly between the two traces so that a little part of each is drawn before going on to the next. When you look at the screen, both signals seem continuous because the scope is "chopping" back and forth at a very fast rate – approximately 250 kHz in the 2200 Series. You can see the chopping if you pick a very fast sweep speed. Move the SEC/DIV switch to 10 μs. Now the display shows broken lines because of the chopping. CHOP is most useful for slow sweep speeds, and ALT for faster sweeps.*

4. *Move the SEC/DIV switch back to 0.5 ms. There's one more vertical mode: ADD. In the add mode, the two signals are algebraically summed (either CH 1 + CH 2, or CH 1 − CH 2 when channel 2 is inverted). To see it in operation, move the right-hand VERTICAL MODE switch to ADD. Now you can see the combined signal roughly halfway between where the two separate signals were.*

CHAPTER 3. THE HORIZONTAL SYSTEM

To draw a graph, your scope needs horizontal as well as vertical data. The horizontal system of your scope supplies the second dimension by providing the deflection voltages to move the electron beam horizontally. And the horizontal system contains a *sweep generator* which produces a sawtooth waveform, or *ramp* (see Figure 7), that is used to control the scope's sweep rates.

It's the sweep generator that makes the unique functions of the modern oscilloscope possible. The circuit that made the rate of rise in the ramp linear — a refinement pioneered by Tektronix — was one of the most important advances in oscillography. It meant that the horizontal beam movement could be calibrated directly in units of time. That advance made it possible for you to measure time between events much more accurately on the scope screen.

Because it is calibrated in time, the sweep generator is often called the *time base*. It lets you pick the time units, observing the signal for either very short times measured in nanoseconds or microseconds, or relatively long times of several seconds.

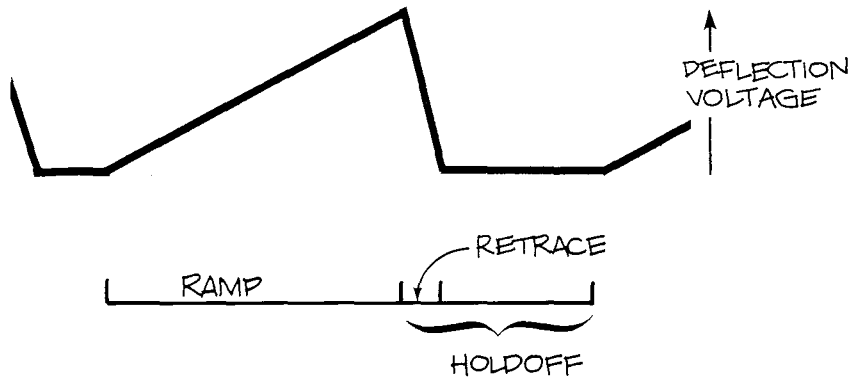


Figure 7.
THE SAWTOOTH WAVEFORM is a voltage ramp produced by the sweep generator. The rising portion of the waveform is called the *ramp;* the falling edge is the *retrace;* and the time between ramps is the *holdoff* time. The sweep of the electron beam across the screen of a scope is controlled by the ramp and the return of the beam to the left side of the screen takes place during the retrace.

The horizontal system controls of a Tektronix 2213 scope are shown in the foldout figure: the horizontal POSITION control is near the top of the panel, and the HORIZONTAL MODE control is below it; the magnification and variable sweep speed control is a red knob in the center of the SEC/DIV switch; at the bottom of the column of horizontal system controls are the DELAY TIME switch and the delay time MULTIPLIER. The dual time base 2215 has two concentric SEC/DIV controls, and a B DELAY TIME POSITION control instead of the delay time switch and multiplier. (The scope controls that you use to position the start of a delayed sweep are also often called *delay time multipliers* or DTMs.)

Horizontal Position

Like the vertical POSITION controls, you use the horizontal POSITION control to change the location of the waveforms on the screen.

Horizontal Operating Modes

Single time base scopes usually have only one horizontal operating mode, but the 2213 offers normal, intensified, or delayed-sweep operating modes. Dual time base scopes like the 2215 usually let you select either of two sweeps. The A sweep is undelayed (like the sweep of a single time base instrument), while the B sweep is started after a delay time. Additionally, some scopes with two time bases — and the 2215 is an example again — let you see the two sweeps at once: the A sweep intensified by the B sweep; and the B sweep itself. This is called an *alternate horizontal operating mode.*

Only the normal horizontal operating mode is used in these first few chapters, so leave your scope's HORIZONTAL OPERATING MODE switch in NO DLY (no delay) on the 2213 and A (for A sweep only) on the 2215. Chapter 9, in the second section of this primer, describes how to make delayed sweep measurements.

Sweep Speeds

The seconds/division switch lets you select the rate at which the beam sweeps across the screen; changing SEC/DIV switch settings allows you to look at longer or shorter time intervals of the input signal. Like the vertical system VOLTS/DIV switch, the control's markings refer to the screen's scale factors. If the SEC/DIV setting is 1 ms, that means that each horizontal major division represents 1 ms and the total screen will show you 10 ms.

On the 2215, which has two time bases, there are two SEC/DIV controls. The A sweep offers all the settings described below; the SEC/DIV switch for the delayed B sweep has settings for 0.05 μs/div to 50 ms/div.

All the instruments of the Tektronix 2200 Series offer sweep speeds from a half-second for each division to 0.05 μs/division. The markings appearing on the scopes are:

.5 s	half a second
.2 s	0.2 second
.1 s	0.1 second
50 ms	50 milliseconds (0.05 second)
20 ms	20 milliseconds (0.02 second)
10 ms	10 milliseconds (0.01 second)
5 ms	5 milliseconds (0.005 second)
2 ms	2 milliseconds (0.002 second)
1 ms	1 millisecond (0.001 second)
.5 ms	half a millisecond (0.0005 second)
.2 ms	0.2 millisecond (0.0002 second)
.1 ms	0.1 millisecond (0.0001 second)
50 μs	50 microseconds (0.00005 second)
20 μs	20 microseconds (0.00002 second)
10 μs	10 microseconds (0.00001 second)
5 μs	5 microseconds (0.000005 second)
2 μs	2 microseconds (0.000002 second)
1 μs	1 microsecond (0.000001 second)
.5 μs	half a microsecond (0.0000005 second)
.2 μs	0.2 microsecond (0.0000002 second)
.1 μs	0.1 microsecond (0.0000001 second)
.05 μs	0.05 microseconds (0.00000005 second)

Scopes also have an XY setting on the SEC/DIV switch for making the X-Y measurements described in Chapter 9.

Variable SEC/DIV
Besides the calibrated speeds, you can change any sweep speed by turning the red CAL control in the center of the SEC/DIV switch counterclockwise. This control slows the sweep speed by at least 2.5:1, making the slowest sweep you have 0.5 seconds x 2.5, or 1.25 seconds/division. Remember that the detent in the extreme clockwise direction is the calibrated position.

Horizontal Magnification
Most scopes offer some means of horizontally magnifying the waveforms on the screen. The effect of magnification is to multiply the sweep speed by the amount of magnification. On 2200 Series scopes there is a 10X horizontal magnification that you engage by pulling out on the red CAL switch. The 10X horizontal magnification gives you a sweep speed ten times faster than the SEC/DIV switch setting; for example, 0.05 μs/division magnified is a very fast 5-nanosecond/division sweep.

The 10X magnification is useful when you want to look at signals and see details that occur very closely together in time.

The DELAY TIME and MULTIPLIER Controls
This switch and dial are used in conjunction with either the intensified or delayed-sweep horizontal operating modes in the 2213. These features are described later under "Delayed Sweep Measurement" in Chapter 9.

The B DELAY TIME POSITION Control
This calibrated 10-turn dial is used to position the beginning of the B sweep relative to the A sweep in a 2215. Its uses are described under "Delayed Sweep Measurements" in Chapter 9.

Using the Horizontal Controls
As you can see in Figure 8, the horizontal system can be divided into two functional blocks: the horizontal amplifier and the sweep generator.

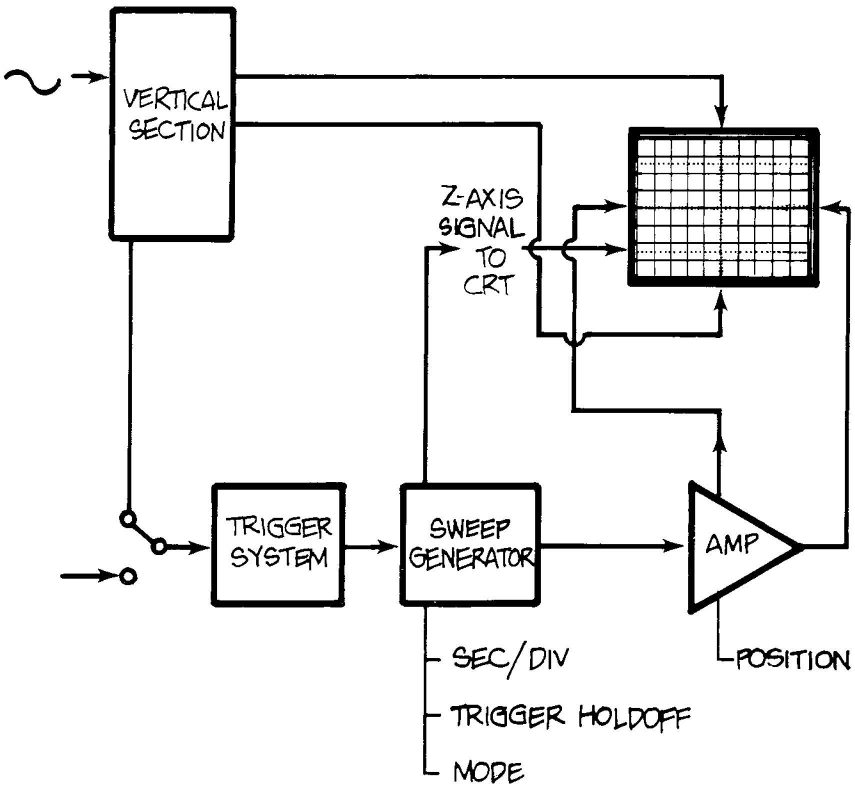


Figure 8.
HORIZONTAL SYSTEM components include the sweep generator and the horizontal amplifier. The sweep generator produces a sawtooth waveform that is processed by the amplifier and applied to the horizontal deflection plates of the CRT. The horizontal system also provides the Z axis of the scope; the Z axis determines whether or not the electron beam is turned on — and how bright it is when it's on.

To familiarize yourself with the horizontal system controls, follow the directions in Exercise 4 and refer to the foldout for control locations. First, make sure the front panel controls have these settings:

- the SEC/DIV switch is on 0.5 ms;
- the trigger SOURCE (A TRIGGER SOURCE on the 2215) is INT; INT (2215: A&B INT) is on CH 1;
- the trigger MODE (2215: A TRIGGER MODE) is AUTO;
- the channel 2 INVERT switch is out (no signal inverting);
- and HORIZONTAL MODE is NO DLY (A on the 2215)

Exercise 4. THE HORIZONTAL SYSTEM CONTROLS

1. *Switch the VERTICAL MODE to CH 1 and the CH 1 VOLTS/DIV setting to 0.5 volt. Be sure your probe is connected to channel 1 and the PROBE ADJ jack. Turn on your scope and move the channel 1 input coupling lever to GND and center the signal on the screen with the POSITION control. Switch to AC coupling.*

2. *Now you can use the horizontal system of your scope to look at the probe adjustment signal. Move the waveform with the horizontal POSITION control until one rising edge of the waveform is lined up with the center vertical graticule. Examine the screen to see where the leading edge of the next pulse crosses the horizontal center line of the graticule. Count major and minor graticule markings along the center horizontal graticule and remember the number.*

3. *Change sweeps to 0.2 ms, line up a rising edge with the vertical graticule on the left edge of the screen and count to the next rising edge. Because the switch was changed from 0.5 to 0.2 ms, the waveform will look 2.5 times as long as before. Of course, the signal hasn't changed, only the scale factor.*

4. *In the middle of the SEC/DIV switch is the red variable control; in its counterclockwise detent, the settings of the SEC/DIV switch are calibrated. Move the control from its detent to see its effect on the sweep speed. Note that now the cycles of the waveform are approximately two-and-a-half times smaller. Return the CAL control to its detent.*

5. *Move the SEC/DIV switch to 0.5 ms and then pull out the red CAL control. This gives you a 10X magnification of the sweep speed. In other words, every setting on the SEC/DIV switch will result in a sweep that's ten times faster; for example, the sweep now is 0.05 ms/division, not 0.5 ms.*

6. *While your scope is magnifying the probe adjustment signal, use the horizontal POSITION control. Its range is now magnified as well, and the combination of magnified signal and POSITION control gives you the ability to examine small parts of a waveform in great detail. Return your scope to its normal sweep speed range by pushing the CAL switch in.*

CHAPTER 4. THE TRIGGER SYSTEM

So far you've found that the display system draws the waveforms on the screen, the vertical system supplies the vertical information for the drawing, and the horizontal system provides the time axis. In other words, you know how the oscilloscope draws a graph; the only thing missing is the "when": when should the other circuits of your scope start drawing the signal, and when shouldn't they?

The when is the trigger and it's important for a number of reasons. First, because getting time-related information is one of the reasons you use a scope. Equally important is that each drawing start with the same "when."

Obviously the graph drawn on the screen isn't the same one all the time you're watching. If you're using the 0.05 μs SEC/DIV setting, the scope is drawing 1 graph every 0.5 μs (0.05 μs/division times ten screen divisions). That's 2,000,000 graphs every minute (not counting retrace and holdoff times, which we'll get to shortly). Imagine the jumble on the screen if each sweep started at a different place on the signal.

But each sweep does start at the right time — if you make the right trigger system control settings. Here's how it's done. You tell the trigger circuit which trigger signal to select with the source switches. With an external signal, you connect the trigger signal to the trigger system circuit with the external coupling controls. Next you set the trigger circuit to recognize a particular voltage level on the trigger signal with the slope and level controls. Then everytime that level occurs, the sweep generator is turned on. The process is diagrammed in Figure 9.

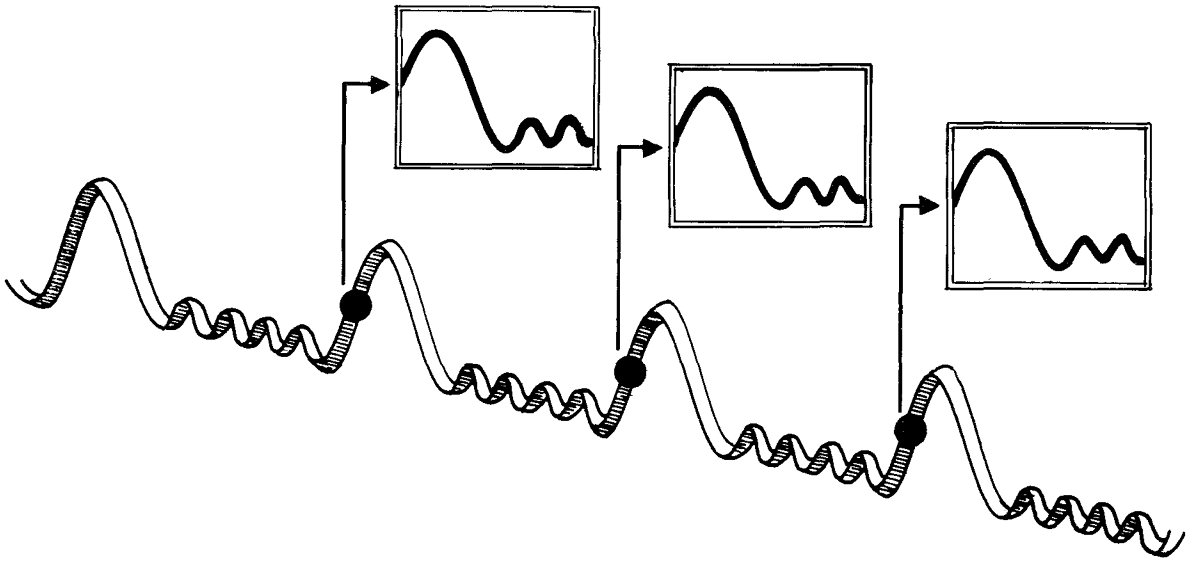


Figure 9.
TRIGGERING GIVES YOU A STABLE DISPLAY because the same trigger point starts the sweep each time. Slope and level controls define the trigger points on the trigger signal. When you look at a waveform on the screen, you're seeing all those sweeps overlaid into what appears to be one picture.

Instruments like those in the Tektronix 2200 Portable Oscilloscope family offer a variety of trigger controls. Besides those already mentioned, you also have controls that determine how the trigger system operates (trigger operating mode) and how long the scope waits between triggers (holdoff).

The control positions are illustrated by the foldout at the end of the primer. All are located on the far right of the front panel. On the 2213, the variable trigger holdoff (VAR HOLDOFF) is at the top, and immediately below it is the trigger MODE switch. Below that the trigger SLOPE and LEVEL controls are grouped. Then a set of three switches controls the trigger sources and the external trigger coupling. At the bottom of the column of trigger controls is the external trigger input BNC connector.

On dual time base 2215 scopes, there is a slightly different control panel layout because you can have a separate trigger for the B sweep.

Trigger Level and Slope
These controls define the trigger point. The SLOPE control determines whether the trigger point is found on the rising or the falling edge of a signal. The LEVEL control determines where on that edge the trigger point occurs. See Figure 10.

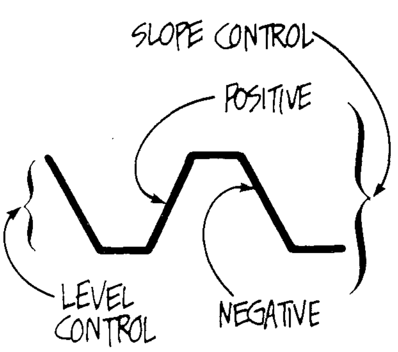


Figure 10.
SLOPE AND LEVEL CONTROLS determine where on the trigger signal the trigger actually occurs. The SLOPE control specifies either a positive (also called the *rising* or *positive-going)* edge or on a negative *(falling* or *negative-going)* edge. The LEVEL control allows you to pick where on the selected edge the trigger event will take place.

Variable Trigger Holdoff

Not every trigger event can be accepted as a trigger. The trigger system will not recognize a trigger during the sweep or the retrace, and for a short time afterward called the *holdoff period.* The retrace, as you remember from the last chapter, is the time it takes the electron beam to return to the left side of the screen to start another sweep. The holdoff period provides additional time beyond the retrace that is used to ensure that your display is stable, as illustrated by Figure 11.

Sometimes the normal holdoff period isn't long enough to ensure that you get a stable display; this possibility exists when the trigger signal is a complex waveform with many possible trigger points on it. Though the waveform is repetitive, a simple trigger might get you a series of patterns on the screen instead of the same pattern each time. Digital pulse trains are a good example; each pulse is very much like any other, so there are many possible trigger points, not all of which result in the same display.

What you need now is some way to control when a trigger point is accepted. The variable trigger holdoff control provides the capability. (The control is actually part of the horizontal system — because it adjusts the holdoff time of the sweep generator — but its function interacts with the trigger controls.) Figure 12 diagrams a situation where the variable holdoff is useful.

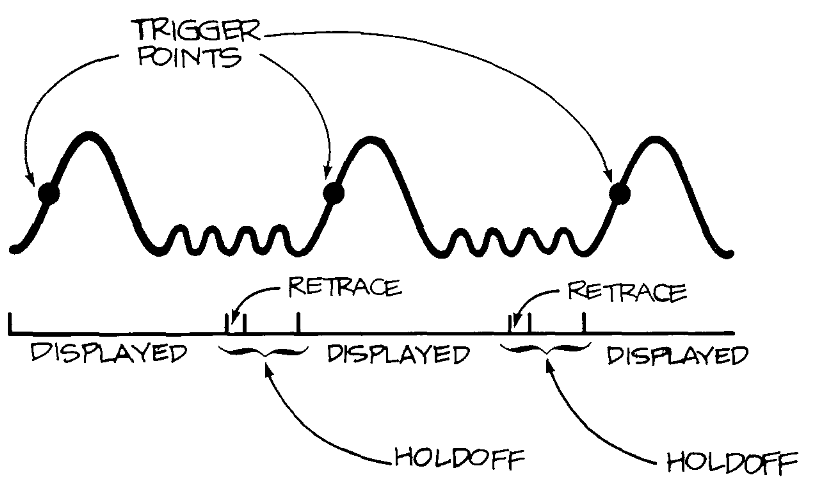


Figure 11.
TRIGGER HOLDOFF TIME ensures valid triggering. In the drawing only the labeled points start the display because no trigger can be recognized during the sweep or the retrace and holdoff period. The retrace and holdoff times are necessary because the electron beam must be returned to the left side of the screen after the sweep, and because the sweep generator needs reset time. The CRT Z axis is *blanked* between sweeps and *unblanked* during sweeps.

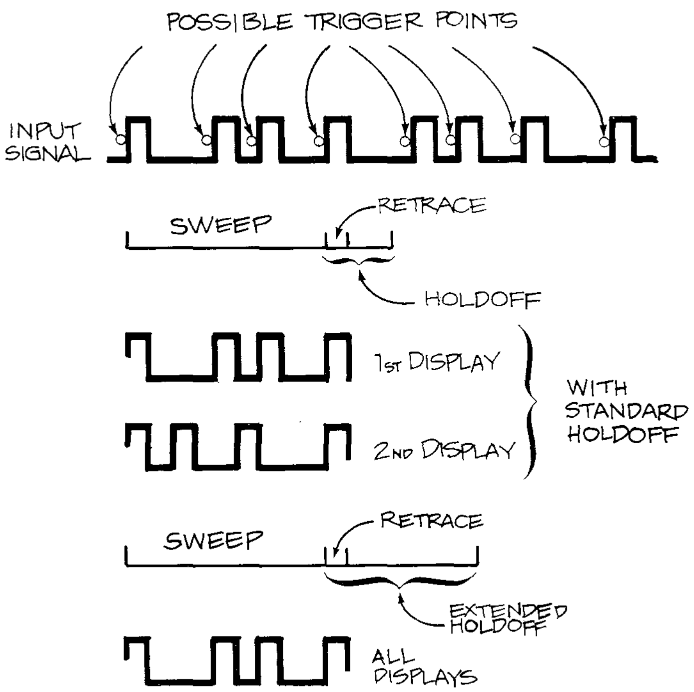


Figure 12.
THE VARIABLE HOLDOFF CONTROL lets you make the scope ignore some potential trigger points. In the example, all the possible trigger points in the input signal would result in an unstable display. Changing the holdoff time to make sure that the trigger point appears on the same pulse in each repetition of the input signal is the only way to ensure a stable waveform.

Trigger Sources

Trigger sources are grouped into two categories that depend on whether the trigger signal is provided internally or externally. The source makes no difference in how the trigger circuit operates, but internal triggering usually means your scope is triggering on the same signal that it is

displaying. That has the obvious advantage of letting you see where you're triggering.

Two switches on the front panel (labeled SOURCE and INT) determine the trigger source. The internal triggering sources are enabled when you move the SOURCE lever to INT. In this position, you can trigger the scope on the signal from either channel, or you can switch to VERT MODE.

Triggering on one of the channels works just like it sounds: you've set the scope to trigger on some part of the waveform present on that channel.

Using the VERTICAL MODE setting on the internal source switch means that the scope's VERTICAL MODE switches determine what signal is used for triggering. If the VERTICAL MODE switches are set at CH 1, then the signal on channel 1 triggers the scope. If you're looking at channel 2, then that channel triggers it. If you switch to the alternate vertical mode, then the scope looks for triggers alternately on the two channels. If the vertical mode is ADD, then CH 1 + CH 2 is the triggering signal. And in the CHOP vertical mode, the scope triggers the same as in ADD, which prevents the instrument from triggering on the chop frequency instead of your signals.

You can see that vertical mode triggering is a kind of automatic source selection that you can use when you must switch back and forth between vertical modes to look at different signals.

But triggering on the displayed signal isn't always what you need, so external triggering is also available. It often gives you more control over the display. To use an external trigger, you set the SOURCE switch to its EXT position and connect the triggering signal to the BNC connector marked EXT INPUT on the front panel. Occasions when external triggering is useful often occur in digital design and repair; there you might want to look at a long train of very similar pulses while triggering with an external clock or with a signal from another part of the circuit.

The LINE position on the SOURCE switch gives you another triggering possibility: the power line. Line triggering is useful anytime you're looking at circuits that are dependent on the power line frequency. Examples include devices like light dimmers and power supplies.

These are all the trigger source possibilities on a 2200 Series scope:

	Switch Positions	
Trigger Source	SOURCE	INT
channel 1 only	INT	CH 1
channel 2 only	INT	CH 2
external	EXT	disabled
line	LINE	disabled
vertical mode (either channel 1 or 2 or both)	INT	VERT MODE

Trigger Operating Modes

The 2200 Series trigger circuits can operate in four modes: normal, automatic, television, and vertical mode.

One of the most useful is the normal trigger mode (marked NORM on the MODE switch) because it can handle a wider range of trigger signals than any other triggering mode. The normal mode does not permit a trace to be drawn on the screen if there's no trigger. The normal mode gives you the widest range of triggering signals: from DC to 60 MHz.

In the automatic (or "bright baseline") mode (labeled AUTO on the front panel): a trigger starts a sweep; the sweep ends and the holdoff period expires. At that point a timer begins to run; if another trigger isn't found before the timer runs out, a trigger is generated anyway causing the bright baseline to appear even when there is no waveform on the channel. In the 2200 Series, the automatic mode is a signal-seeking auto mode. This means that for most of the signals you'll be measuring, the auto mode will match the trigger level control to the trigger signal. That makes it most unlikely that you will set the trigger level control outside of the signal range. The auto mode lets you trigger on signals with changing voltage amplitudes or waveshapes without making an adjustment of the LEVEL control.

Another useful operating mode is television triggering. Most scopes with this mode let you trigger on tv fields at sweeps of 100 μs/division and slower, and tv lines at 50 μs/div or faster. With a 2200 Series scope, you can trigger on either fields or lines at any sweep speed; for tv field triggering, use the TV FIELD switch position, and for television line triggering, use the NORM or AUTO settings.

You'll probably use the normal and automatic modes the most often. The AUTO because it's essentially totally automatic, and normal because it's the most versatile. For example, it's possible to have a low frequency signal with a repetition rate that is mismatched to the run-out of an automatic mode timer; when that happens the signal will not be steady in the auto mode. Moreover, the automatic signal-seeking mode can't trigger on very low frequency trigger signals. The normal mode, however, will give you a steady signal at any rep rate.

The last 2200 Series trigger operating mode, the vertical mode, is unique in its advantages. Selecting the VERT MODE position on the INT switch automatically selects the trigger source as you read in "Trigger Source" above. It also makes alternate triggering possible. In this operating mode, the scope triggers alternately on the two vertical channels. That means you can look at two completely unrelated signals. Most scopes only trigger on one channel or the other when the two signals are not synchronous.

Here's a review of the 2200 trigger modes:

Trigger Operating Mode	Switch Settings
normal	NORM on the MODE switch
automatic	AUTO on the MODE switch
television field	TV FIELD on the MODE switch
television line	NORM or AUTO on the MODE switch
vertical mode	VERT MODE on the INT switch

Triggering Coupling

Just as you may pick either alternating or direct coupling when you connect an input signal to your scope's vertical system, you can select the kind of coupling you need when you connect a trigger signal to the trigger system's circuits. For internal triggers, the vertical input coupling selects the trigger coupling. For external trigger signals, however, you must select the coupling you want:

Coupling	Applications
DC	DC couples all elements of the triggering signal (both AC and DC) to the trigger circuit.
DC with attenuation	If you want DC coupling and the external trigger is too large for the trigger system, move the TRIGGER COUPLING switch to its DC÷10 setting.
AC	This coupling blocks DC components of the trigger signal and couples only the AC components.

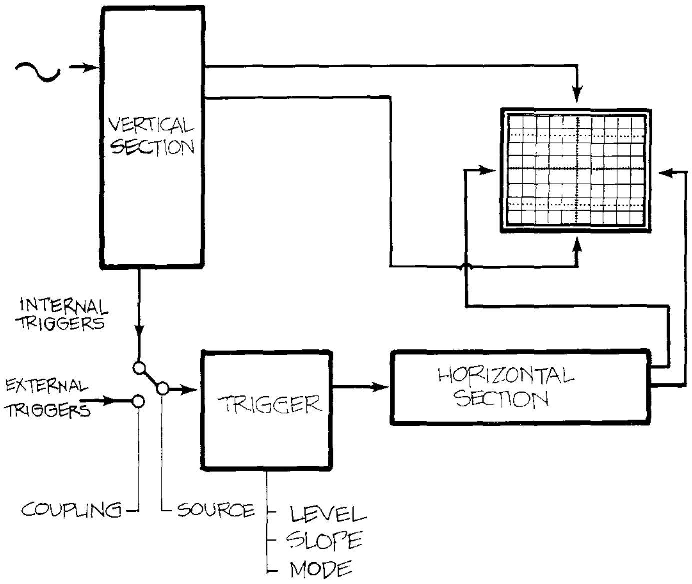


Figure 13.
THE TRIGGER CIRCUIT AND ITS CONTROLS are shown in the diagram above. Trigger source describes whether or not the trigger signal is internal or external to the scope. Coupling controls the connection of an external trigger to the trigger circuit. The level and slope controls determine where the trigger point will be on the trigger signal. And the mode control determines the operations of the trigger circuit.

Using the Trigger Controls

To review what you've learned about the trigger circuit and its controls (shown schematically in Figure 13), first make sure all your controls are in these positions:

- 0.5 VOLTS/DIV on channel 1 and CAL in its detent position;
- AC vertical coupling;
- CH 1 on the VERTICAL MODE switch;
- 0.5 ms sweep speed and no magnification or variable SEC/DIV;
- your trigger settings should be AUTO for MODE, INT for SOURCE, and CH 1 for INT

Turn your scope on with the probe connected to the channel 1 BNC connector and the probe adjustment jack. Use the foldout figure to remind yourself of the control locations and follow the directions in Exercise 5.

Exercise 5. TRIGGER CONTROLS

1. *Move the trace to the right with the horizontal POSITION control until you can see the beginning of the signal (you'll probably have to increase the intensity to see the faster vertical part of the waveform). Watch the signal while you operate the SLOPE control. If you pick +, the* signal on the screen starts with a rising edge; the other SLOPE control position makes the scope trigger on a falling edge.

2. *Now move the LEVEL control back and forth through all its travel; you'll see the leading edge climb up and down the signal. The scope remains triggered because you are using the AUTO setting.*

3. *Turn the MODE switch to NORM. Now when you use the LEVEL control to move the trigger point, you'll find places where the scope is untriggered. This is an illustration of the essential difference between normal and automatic triggering.*

4. *You can also see the difference between the two triggering modes by using channel 2, even with that channel coupled to GND for ground. Change both the vertical display mode and the INT (2215:A&B INT) switches to CH 2. With NORM triggering, there's no signal; with AUTO, you'll see the baseline. Try it.*

5. *Without a trigger signal applied to the EXT INPUT BNC connector, it's impossible to show you the use of this trigger source, but the trigger MODE, SLOPE, and LEVEL controls will all operate the same for either internal or external triggers. One difference between internal and external sources, however, is the sensitivity of the trigger circuit. All external sources are measured in voltage (say, 150 millivolts) while the internal sources are rated in divisions. In other words, for internal signals, the displayed amplitude makes a difference. Now change the VERTICAL MODE and INT switches back to CH 1, and switch to the NORM mode. Use the LEVEL control and notice how much control range there is. Now change the CH 1 VOLTS/DIV switch to 0.1 V and use the LEVEL control. There's more control range now.*

6. *The alternate-channel triggering with vertical mode triggering can't be demonstrated without two unrelated signals on the channels, but you'll find it useful the first time such an occasion comes up. You can take another look at the difference between the normal and auto trigger operating modes. Move the LEVEL control slowly in the NORM mode until the scope is untriggered. Now switch the trigger operating mode to AUTO and note that the waveform is automatically triggered.*

CHAPTER 5. ALL ABOUT PROBES

Connecting all the measurement test points you'll need to the inputs of your oscilloscope is best done with a probe like the one illustrated in Figure 14. Though you could connect the scope and circuit-under-test with just a wire, this simplest of all possible connections would not let you realize the full capacities of your scope. The connection would probably load the circuit and the wire would act as an antenna and pick up stray signals — 60 Hz power, CBers, radio and tv stations — and these would be displayed on the screen along with the signal of interest.

Circuit Loading

Using a probe instead of a bare wire minimizes stray signals, but there's still an effect from putting a probe in a circuit called *circuit loading*. Circuit loading modifies the environment of the signals in the circuit you want to measure; it changes the signals in the circuit-under-test, either a little or lot, depending on how great the loading is.

Circuit loading is resistive, capacitive, and inductive. For signal frequencies under 5 kHz, the most important component of loading is resistance. To avoid significant circuit loading here, all you need is a probe with a resistance at least two orders of magnitude greater than the circuit impedance (100 MΩ probes for 1 MΩ sources; 1 MΩ probes for 10 kΩ sources, and so on).

When you are making measurements on a circuit that contains high frequency signals, inductance and capacitance become important. You can't avoid adding capacitance when you make connections, but you can avoid adding more capacitance than necessary.

One way to do that is to use an attenuator probe; its design greatly reduces loading. Instead of loading the circuit with capacitance from the probe tip plus the cable plus the scope's own input, the 10X attenuator probe introduces about ten times less capacitance, as little as 10-14 picofarads (pF). The penalty is the reduction in signal amplitude from the 10:1 attenuation.

These probes are adjustable to compensate for variations in oscilloscope input capacitance and your scope has a reference signal available at the front panel. Making this adjustment is called *probe compensation* and you did it as the first step in Exercise 3 of Chapter 2.

Remember when you are measuring high frequencies, that the probe's impedance (resistance and reactance) changes with frequency. The probe's specification sheet or manual will contain a chart like that in Figure 15 that shows this change. Another point to remember when making high frequency measurements is to be sure to securely ground your probe with as short a ground clip as possible. As a matter of fact, in some very high frequency applications a special socket is provided in the circuit and the probe is plugged into that.

Measurement System Bandwidth

Then there is one more probe characteristic to consider: bandwidth. Like scopes, probes have bandwidth limitations; each has a specified range within which it does not attenuate the signal's amplitude more than −3 dB (0.707 of the original value). But don't assume that a 60 MHz probe and a 60 MHz scope give you a 60 MHz measurement capability. The combination will approximately equal the square root of the sum of the squares of the rise times (also see Chapter 10).

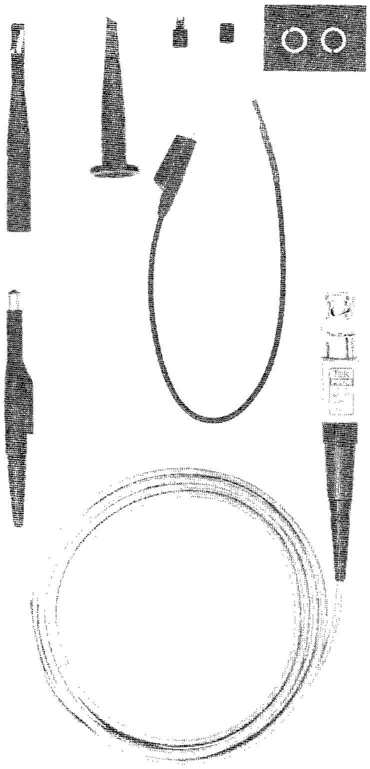


Figure 14.
PROBES CONNECT THE SCOPE AND THE CIRCUIT-UNDER-TEST. Tektronix probes consist of a patented resistive cable and a grounded shield. Two P6120 probes and the accessories pictured above are supplied with every 2200 Series scope. The probe is a high impedance, minimum loading 10 X passive probe. The accessories for each probe (from left to right) are: a grabber tip for ICs and small diameter leads; a retractable hook tip; and IC tester tip cover; an insulating ground cover; marker bands; and (in the center) the ground lead.

For example, if both probe and scope have rise times of 5.83 nanoseconds:

$$T_{r\,(system)} = \sqrt{T_{r\,(scope)}^2 + T_{r\,(probe)}^2}$$

$$T_r = \sqrt{34 + 34}$$

That works out to 8.25 nanoseconds, the equivalent to a bandwidth of 42.43 MHz because:

$$BW_{(megahertz)} = \frac{350}{T_{r\,(nanoseconds)}}$$

To get the full bandwidth from your scope, you need more bandwidth from the probe. Or you use the particular probe designed for that instrument. For example, in the case of the 2200 Series scopes and the P6120 10X Passive Probe, the probe and the scope have been designed to function together and you have the full 60 MHz bandwidth at the probe tip.

Probe Types

Generally you can divide probes by function, into voltage-sensing and current-sensing types. Then voltage probes can be further divided into passive and active types. One of these should meet your measurement requirements.

PROBE TYPES	CHARACTERISTICS
1X passive, voltage-sensing	No signal reduction, which allows the maximum sensitivity at the probe tip; limited bandwidths: 4-34 MHz; high capacitance: 32-112 pF; signal handling to 500 V
10X/100X/1000X passive, voltage-sensing, attenuator	Attenuates signals; bandwidths to 300 MHz; adjustable capacitance; signal handling to 500 V (10X), 1.5 kV (100X), or 20 kV (1000X)
active, voltage-sensing, FET	Switchable attenuation; capacitance as low as 1.5 pF; more expensive, less rugged than other types; limited dynamic range; but, bandwidths to 900 MHz; minimum circuit loading
current-sensing	Measure currents from 1 mA to 1000 A; DC to 50 MHz; very low loading
high voltage	Signal handling to 40 kV

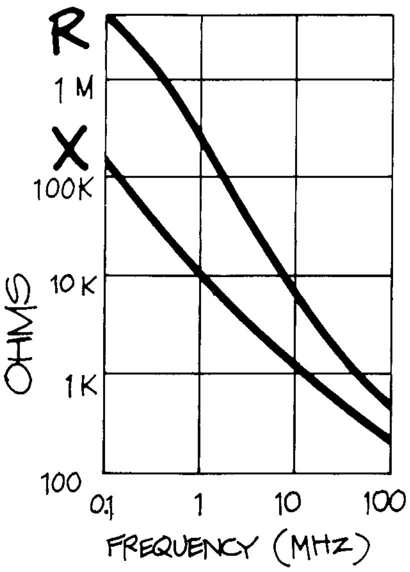


Figure 15.
PROBE IMPEDANCE IS RELATED TO FREQUENCY as shown in the table above. The curves plot both resistance (R) and reactance (X) in ohms against frequency in megahertz. The plot shown is for the Tektronix P6120 probe on a 1-meter cable.

Picking A Probe

For most applications, the probes that were supplied with your scope are the ones you should use. These will usually be attenuator probes. Then, to make sure that the probe can faithfully reproduce the signal for your scope, the compensation of the probe should be adjustable. If you're not going to use the probes that came with your scope, pick your probe based on the voltage you intend to measure. For example, if you're going to be looking at a 50 volt signal and your largest vertical sensitivity is 5 volts, that signal will take up ten major divisions of the screen. This is a situation where you need attenuation; a 10X probe would reduce the amplitude of your signal to reasonable proportions.

Proper termination is important to avoid unwanted reflections of the signal you want to measure within the cable. Probe/cable combinations designed to drive 1 megohm (1 MΩ) inputs are engineered to suppress these reflections. But for 50 Ω scopes, 50 Ω probes should be used. The proper termination is also necessary when you use a coaxial cable instead of a probe. If you use a 50 Ω cable and a 1 MΩ scope, be sure you also use a 50 Ω terminator at the scope input.

The probe's ruggedness, its flexibility, and the length of the cable can also be important (but remember, the more cable length, the more capacitance at the probe tip). And check the specifications to see if the bandwidth of the probe is sufficient, and make sure you have the adapters and tips you'll need. Most modern probes feature interchangeable tips and adaptors for many applications. Retractable hook tips let you attach the probe to most circuit components. Other adaptors connect probe leads to coaxial connectors or slip over square pins. Alligator clips for contacting large diameter test points are another possibility.

But for the reasons already mentioned (probe bandwidth, loading, termination), the best way to ensure that your scope and probe measurement system has the least effect on your measurements is to use the probe recommended for *your* scope. And always make sure it's compensated.

PART II. MAKING MEASUREMENTS

The first five chapters described how to select the exact oscilloscope functions you need to make the measurements you want. Now you can put what you've learned into practice with this section of the primer.

It begins with a review of waveform shapes and characteristics in Chapter 6. Then the discussions in Chapter 7 start with safety because you should always observe safety precautions when working on electrical equipment.

The first step in ensuring accurate measurements is making sure your scope is set up properly, and this subject is discussed in Chapter 8.

Chapter 9 discusses measurement techniques, beginning with fundamental time and amplitude measurements and ending with delayed sweep measurements.

The last chapter in the primer describes oscilloscope performance and how it affects your measurements.

CHAPTER 6. WAVEFORMS

The definition of a *wave* is "a disturbance traveling through a medium" while the definition of a *waveform* is "a graphic representation of a wave."

Like a wave, a waveform is dependent on two things: movement and time. The ripple on the surface of a pond exists as a movement of water in time. The waveform on your scope's screen is the movement of an electron beam during time.

The changes in the waveform with time form the waveshape, the most readily identifiable characteristic of a waveform. Figure 16 illustrates some common waveshapes.

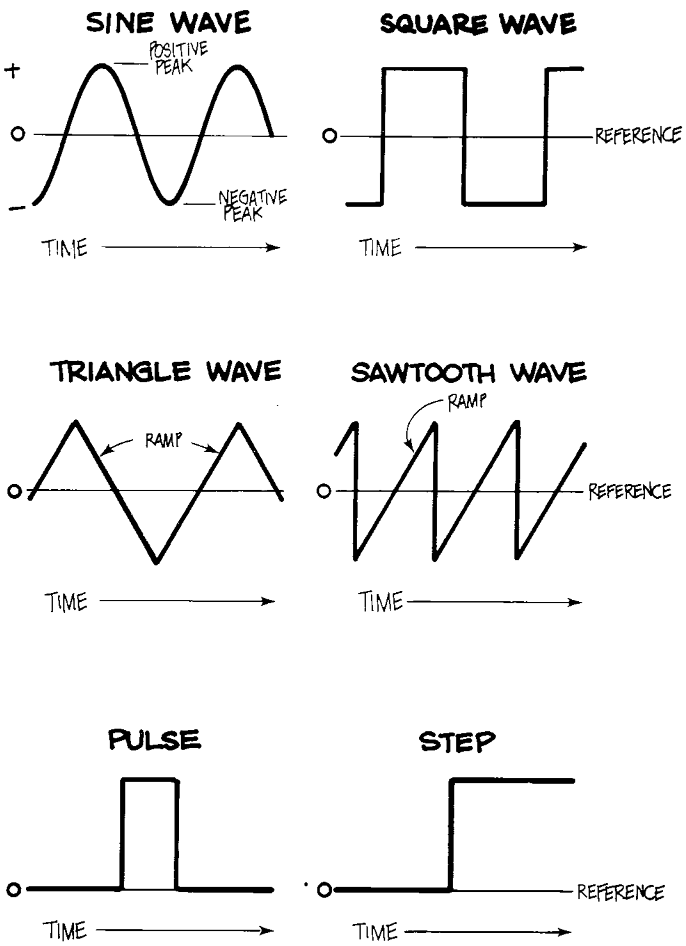


Figure 16.
BASIC WAVESHAPES include *sine waves*, and various non-sinusoidal waves such as *triangle waves, square waves*, and *sawtooth waves*. A square wave has equal amounts of time for its two states. Triangle and sawtooth waves are usually the result of circuits designed to control voltage with respect to time, like the sweep of an oscilloscope and some television circuits. In these waveforms, one (or both) transitions from state to state are made with a steady variation at a constant rate, a *ramp*. (Changes from one state to another on all waveforms except sine waves are called *transitions*.) The last two drawings represent aperiodic, single-shot waveforms. The first is a *pulse;* all pulses are marked by a rise, a finite duration, and a decay. The second one is a *step*, which is actually a single transition.

MAKING MEASUREMENT CONT.

Waveshapes tell you a great deal about the signal. Anytime you see a change in the vertical dimension of a signal, you know that this amplitude change represents a change in voltage. Anytime there's a flat horizontal line, there was no change for that length of time. Straight diagonal lines mean a linear change, equal rise (or fall) of voltage for equal amounts of time. Sharp angles on a waveform mean a sudden change. But waveshapes alone are not the whole story. When you want to completely describe a waveform, you'll want to find the parameters of that particular waveform. Depending on the signal, these parameters might be amplitude, period, frequency, width, rise time, or phase. You can review these signal parameters with Figures 17 through 22.

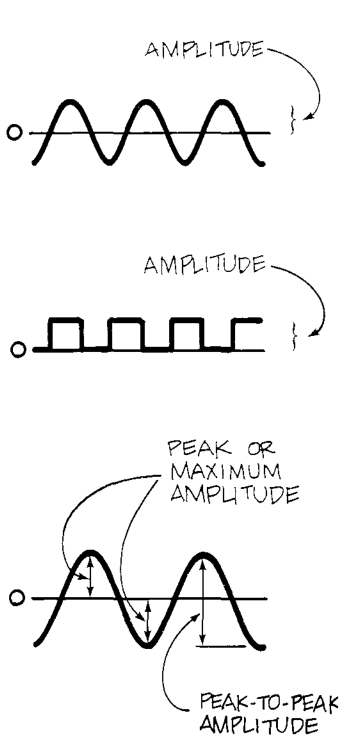


Figure 17.
AMPLITUDE IS A CHARACTERISTIC OF ALL WAVEFORMS. It is the amount of displacement from equilibrium at a particular point in time. Note that without a modifier, the word means the maximum change from a reference without regard to the direction of the change. In the first two drawings above (sine wave and square wave), the amplitude is the same even though the sine wave is larger from peak to peak. In the third drawing, an alternating current waveform is shown with peak (or maximum) amplitude and peak-to-peak amplitude parameters annotated. In oscilloscope measurements, amplitude usually means peak-to-peak amplitude.

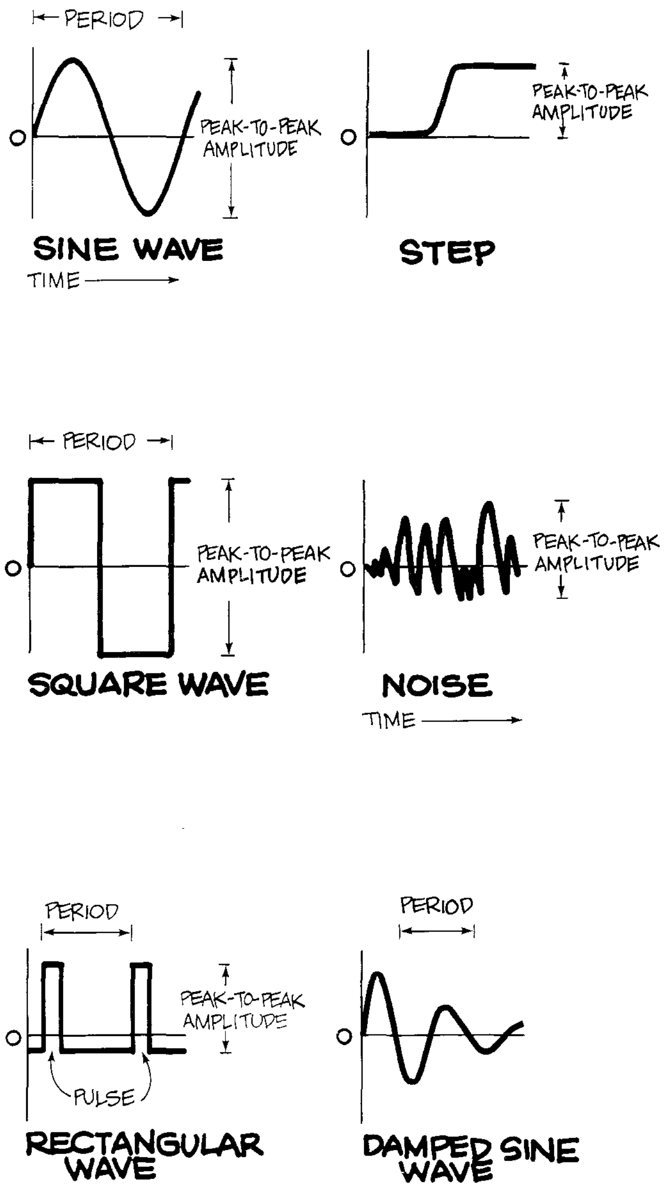


Figure 18.
PERIOD IS THE TIME REQUIRED FOR ONE CYCLE OF A SIGNAL if the signal repeats itself. Period is a parameter whether the signal is symmetrically shaped like the sine and square waves above, or whether it has a more complex and asymmetrical shape like the rectangular wave and damped sine wave. Period is always expressed in units of time. Naturally, one-time signals like the step or uncorrelated signals (without a time relation) like noise have no period.

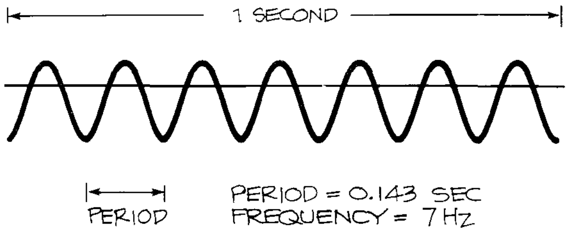


Figure 19.
IF A SIGNAL IS PERIODIC, IT HAS A FREQUENCY. Frequency is the number of times a signal repeats itself in a second; frequency is measured in Hertz: 1 Hz = 1 cycle per second; 1 kHz (kilohertz) = 1000 cycles/second; and 1 MHz (megahertz) = 1,000,000 cycles/second. Period and frequency are reciprocal: 1/period = frequency, and 1/frequency = period. For example, a 7 Hz signal has a period of 0.143 seconds: 1/7 Hz = 0.143 s, and 1/0.143 s = 7 Hz.

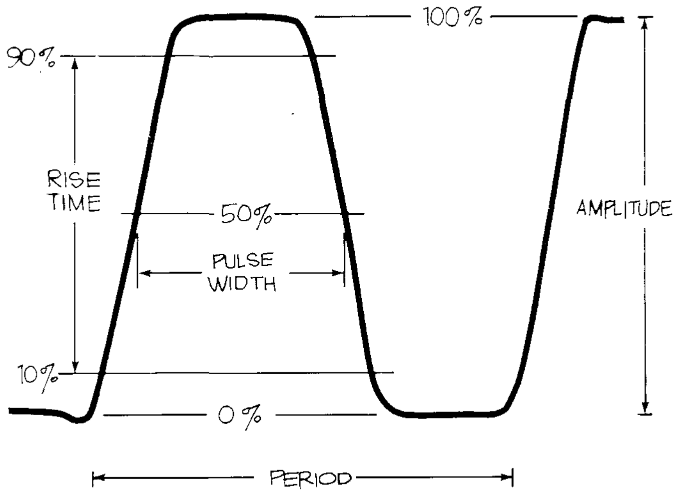


Figure 20.
THE PARAMETERS OF A PULSE can be important in a number of different applications. Digital circuitry, X-ray equipment, and data communications are examples. Pulse specifications include transition times measured on the leading edge of a positive-going transition; this is the *rise time*. *Fall time* is the transition time on a negative-going trailing edge. *Pulse width* is measured at the 50% points and amplitude from 0 to 100%. Any displacement from 0 volts for the base of the pulse is the *baseline offset*.

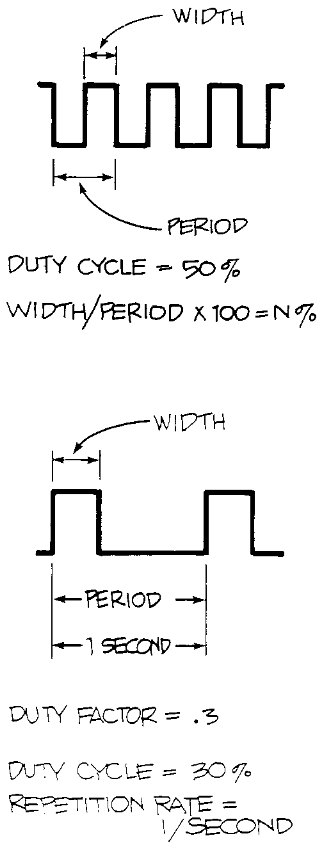


Figure 21.
DUTY CYCLE, DUTY FACTOR, AND REPETITION RATE are parameters of all rectangular waves. They are particularly important in digital circuitry. *Duty cycle* is the ratio of pulse width to signal period expressed as a percentage. For square waves, it's always 50% as you can see; for the pulse wave in the second drawing, it's 30%. *Duty factor* is the same thing as duty cycle except it is expressed as a decimal, not a percentage. A *repetition rate* describes how often a pulse train occurs and is used instead of frequency to describe waveforms like that in the second drawing.

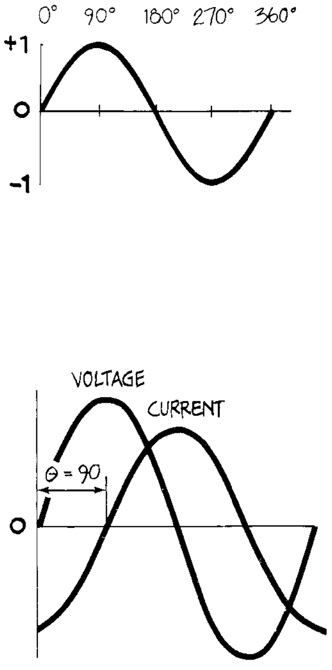


Figure 22.
PHASE is best explained with a sine wave. Remember that this waveform is based on the sine of all the angles from 0 through 360. The result is a plot that changes from 0 to 0°, 1 at 90°, 0 again at 180°, −1 at 270°, and finally 0 again at 360°. Consequently, it is useful to refer to the *phase angle* (or simply *phase*, when there is no ambiquity) of a sine wave when you want to describe how much of the period has elapsed. Another use of phase is found when you want to describe a relationship between two signals. Picture two clocks with their second hands sweeping the dial every 60 seconds. If the second hands touch the twelve at the same time, the clocks are *in phase;* if they don't, then they're *out of phase*. To express how far out of phase they are, you use *phase shift* in degrees. To illustrate, the waveform labeled CURRENT in the drawing above is said to be 90° out of phase with the voltage waveform. Other ways of reporting the same information are "the current waveform has a 90 degree phase angle with respect to the voltage waveform" or "the current waveform lags the voltage waveform by 90°." Note that there is always a reference to another waveform; in this case, between the voltage and current waveforms of an inductor.

CHAPTER 7. SAFETY

Before you make any oscilloscope measurement, remember that you must be careful when you work with electrical equipment. Always observe *all* safety precautions described in the operators or service manual for the equipment you're working on.

Some general rules about servicing electrical equipment are worth repeating here. Don't service electrical devices alone. Know the symbols for dangerous circuits and observe the safety instructions for the equipment you're working on. Don't operate an electrical device in an explosive atmosphere. Always ground the scope to the circuit, and ground both your scope and the circuit-under-test. Remember that if you lose the ground, all accessible conductive parts — including knobs that appear to be insulated — can give you a shock. To avoid personal injury, don't touch exposed connections and components in the circuit-under-test when the power is on. And remember to consult the service manual for the equipment you're working on.

Then there are few rules about the scope itself: To avoid a shock, plug the power cord of the scope into a properly-wired receptacle before connecting your probes; only use the power cord for your scope, and don't use one that isn't in good condition (cracked, broken, missing ground pin, etc.). Use the right fuse to avoid fire hazards. Don't remove covers and panels on your scope.

CHAPTER 8. GETTING STARTED

Accurate oscilloscope measurements require that you make sure your system is properly setup each time you begin to use your scope.

Compensating the Probe

Most measurements you make with an oscilloscope require an *attenuator probe,* which is any probe that reduces voltage. The most common are 10X ("times ten") passive probes which reduce the amplitude of the signal and the circuit loading by 10:1.

But before you make any measurement with an attenuator probe, you should make sure it's compensated. Figure 23 illustrates what can happen to the waveforms you'll see when the probe is not properly compensated.

Note that you should compensate your probe as it will be used when you make the measurement. Compensate it with the accessory tip you'll be using and don't compensate the probe in one vertical channel and then use it on another.

Checking the Controls

The most common mistake in making oscilloscope measurements is forgetting to compensate the probe. The second most frequent source of inaccuracies is forgetting to check the controls to make sure they're where you think they are. Here are some things to check on your Tektronix 2200 Series scope (arranged according to the functional blocks of your scope):

- Check all the vertical system controls: variable controls (CH 1 and CH 2 VOLTS/DIV CAL) should be in their calibrated detent positions; make sure CH 2 isn't inverted (unless you want it to be); check the vertical mode switches to make sure the signal from the proper channel(s) will be displayed; check the two vertical system VOLTS/DIV switches to see if their settings are right (and don't forget to use the VOLTS/DIV readout that matches the probe, either 1X or 10X); check the input coupling levers too.
- Check the horizontal system control settings: magnification is off (push in the red CAL switch in the middle of the SEC/DIV switch); variable SEC/DIV is in its calibrated detent position. Make sure the horizontal mode switch is where you need it: NO DLY when you're not making delayed sweep measurements, INTENS for making measurements with an intensified zone, or DLY'D if you want a delayed sweep (A, ALT, or B on a 2215).
- Then check your trigger system controls to make sure your scope will pick the right slope on the trigger signal, that the right coupling is selected, and that the correct operating mode will be used. Also make sure that the trigger variable holdoff control is at its minimum position.

Handling a Probe

Before you probe a circuit, you should make sure you have the right probe tips and adaptors for the circuits you will be working on. (Tips available for the Tektronix P6120 10X probes were shown in Figure 14, Chapter 5.)

Then make sure that the ground in the circuit-under-test is the same as the scope ground — don't just assume it is. The scope ground will always be earth ground as long as you're using the proper power cord and plug. Check the circuit ground by touching the probe tip to the point you think is ground before you make a hard ground by attaching the ground strap of your probe.

If you're going to be probing a lot of different points in the same circuit and measuring frequencies less than 5 MHz, you can ground that circuit to your scope once instead of each time you move the probe. Connect the circuit ground to the jack marked GND on the front panel.

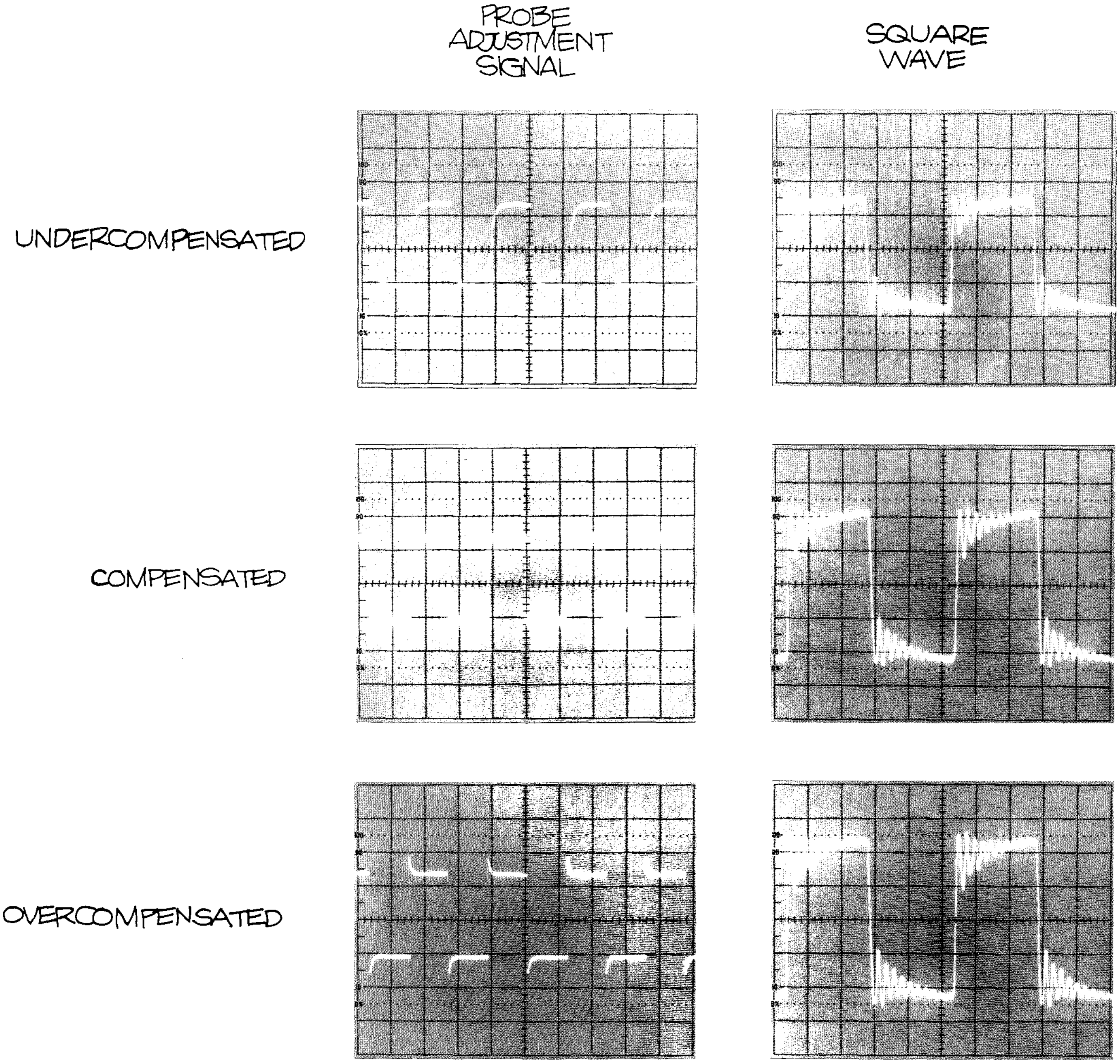


Figure 23.
IMPROPERLY COMPENSATED PROBES can distort the waveforms you see on the screen of your scope. In the photographs the probe adjustment signal and a 1 MHz square wave are shown as they will appear with proper and improper compensations. Notice the amplitude and ringing changes on the square wave with the differences in compensation.

CHAPTER 9. MEASUREMENT TECHNIQUES

Rather than attempt to describe how to make every possible measurement, this chapter describes common measurement techniques you can use in many applications.

The Foundations: Amplitude and Time Measurements
The two most basic measurements you can make are amplitude and time; almost every other measurement you'll make is based on one of these two fundamental techniques.

Since the oscilloscope is a voltage-measuring device, voltage is shown as amplitude on your scope screen. Of course, voltage, current, resistance, and power are related:

$$\text{current} = \frac{\text{voltage}}{\text{resistance}}$$

$$\text{resistance} = \frac{\text{voltage}}{\text{current}}$$

$$\text{power} = \text{current} \times \text{voltage}$$

Amplitude measurements are best made with a signal that covers most of the screen vertically. Use Exercise 6 to practice making amplitude measurements.

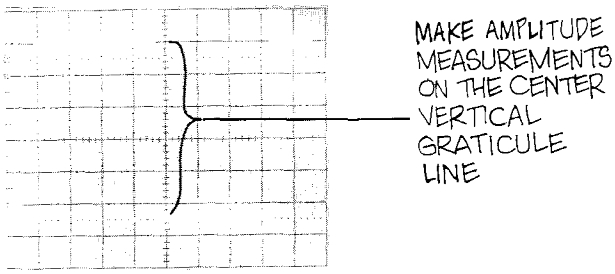
Time measurements are also more accurate when the signal covers a large area of the screen. Continue with the set-up you had for the amplitude measurement, but now use Exercise 7 to make a period measurement.

Exercise 6. AMPLITUDE MEASUREMENTS

1. Connect your probe to the channel 1 BNC connector and to the probe adjustment jack. Attach the probe ground strap to the collar of the channel 2 BNC. Make sure your probe is compensated and that all the variable controls are set in their detent positions.

2. The trigger MODE switch should be set to NORM for normal triggering. The HORIZONTAL MODE should be NO DLY (A on the 2215). Make sure the channel 1 coupling switch is set to AC and that the trigger SOURCE switch is on internal and the INT switch on CH 1. Set the VERTICAL MODE switch to CH 1 as well.

3. Use the trigger LEVEL control to obtain a stable trace and move the volts/division switch until the probe adjust square wave is about five divisions high. Now turn the seconds/division switch until two cycles of the waveform are on your screen. (The settings should be 0.1 V on the VOLTS/DIV and 0.2 ms on the SEC/DIV switches.)

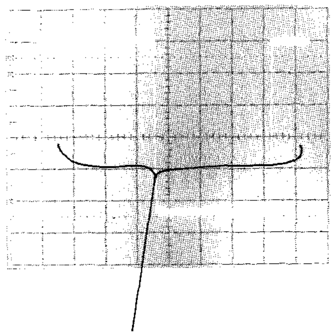


4. Now use the CH 1 vertical POSITION control to move the square wave so that its top is on the second horizontal graticule line from the top edge of the screen. Use the horizontal position control to move the signal so that the bottom of one cycle intersects the center vertical graticule line.

5. Now you can count major and minor divisions down the center vertical graticule line and multiply by the VOLTS/DIV setting to make the measurement. For example, 5.0 divisions times 0.1 volts equals 0.5 volts. (If the voltage of the probe adjustment square wave in your scope is different from this example, that's because this signal is not a critical part of your scope and tight tolerances and exact calibration are not required.)

Exercise 7. TIME MEASUREMENTS

Time measurements are best made with the center horizontal graticule line. Use the instrument settings from Exercise 6 and center the square wave vertically with the vertical POSITION control. Then line up one rising edge of the square wave with the graticule line that's second from the lefthand side of the screen with the HORIZONTAL position control. Make sure the next rising edge intersects the center horizontal graticule. Count major and minor divisions across the center horizontal graticule line from left to right as shown in the photo above. Multiply by the SEC/DIV setting; for example, 5.7 divisions times 0.2 milliseconds equals 1.14 milliseconds. (If the period of the probe adjustment square wave in your scope is different from this example, remember that this signal is not a critical part of the calibration of your scope.)



Frequency and Other Derived Measurements

The voltage and time measurements you just made are two examples of *direct measurements*. Once you've made a direct measurement, there are *derived measurements* you can calculate. Frequency is one example; it's derived from period measurements. While period is the length of time required to complete one cycle of a periodic waveform, frequency is the number of cycles that take place in a second. The measurement unit is a hertz (1 cycle/second) and it's the reciprocal of the period. So a period of 0.00114 second (or 1.14 milliseconds) means a frequency of 877 Hz.

More examples of derived measurements are the alternating current measurements illustrated by Figure 24.

Pulse Measurements

Pulse measurements are important when you work with digital equipment and data communications devices. Some of the signal parameters of a pulse were shown in Figure 20, but that was an illustration of an ideal pulse, not one that exists in the real world. The most important parameters of a real pulse are shown in Figure 25.

Use Exercise 8 to make derived measurements with the probe adjustment square wave.

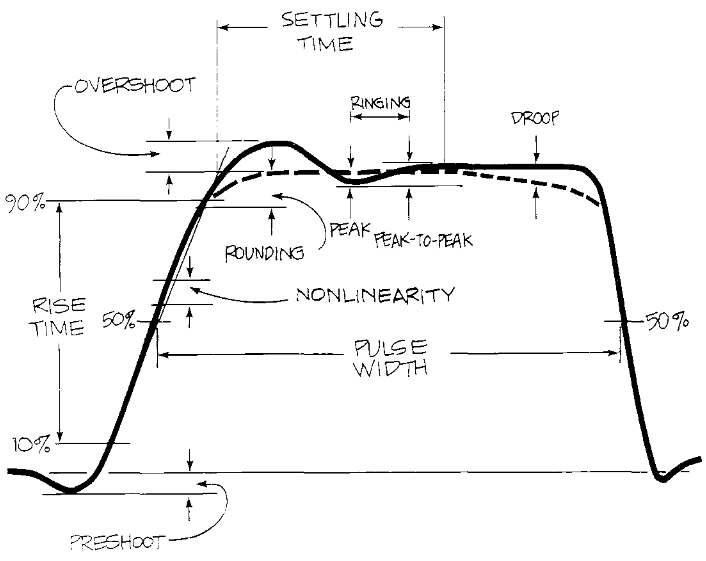


Figure 25.
REAL PULSE MEASUREMENTS include a few more parameters than those for an ideal pulse. In the diagram above, several are shown. Preshooting is a change of amplitude in the opposite direction that precedes the pulse. Overshooting and rounding are changes that occur after the initial transition. Ringing is a set of amplitude changes — usually a damped sinusoid — that follows overshooting. All are expressed as percentages of amplitude. Settling time expresses how long it takes the pulse to reach it maximum amplitude. Droop is a decrease in the maximum amplitude with time. And nonlinearity is any variation from a straight line drawn through the 10 and 90% points of a transition.

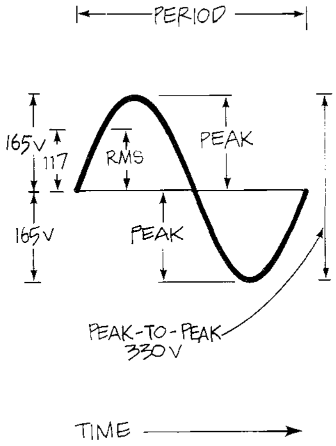


Figure 24.
DERIVED MEASUREMENTS are the result of calculations made after direct measurements. For example, alternating current measurements require an amplitude measurement first. The easiest place to start is with a peak-to-peak amplitude measurement of the voltage — in this case, 330 volts because peak-to-peak measurements ignore positive and negative signs. The *peak voltage* is one-half that (when there is no DC offset), and is also called a *maximum value*; it's 165 V in this case. The *average value* is the total area under the voltage curves divided by the period in radians; in the case of a sine wave, the average value is 0 because the positive and negative values are equal. The RMS (root mean square) voltage for this sine wave — which represents the line voltage in the United States — is equal to the maximum value divided by the square root of 2: 165 ÷ 1.414 = 117 volts. You get from peak-to-peak to RMS voltage with: peak-to-peak ÷ 2 x the square root of 2.

Exercise 8. DERIVED MEASUREMENTS

With the period measurement you just made in Exercise 7, calculate the frequency of the probe adjustment square wave. For example, if the period is 1 millisecond, then the frequency is the reciprocal, 1 0.001 or 1000 Hz. Other derived measurements you can make are duty cycle, duty factor, and repetition rate. Duty cycle is the ratio of pulse width to signal period expressed as a percentage: 0.5 ms ÷ 1 ms, or 50%. But you knew that because for square waves, it's always 50%. Duty factor is 0.5. And the repetition rate (describing how often a pulse train occurs) is 1000 second in this case because repetition rate and frequency are equal for square waves. Your probe adjustment signal might differ slightly from this example; calculate the derived measurements for it. You can also calculate the peak, peak-to-peak, and average values of the probe adjustment square wave in your scope. Don't forget that you need both the alternating and direct components of the signal to make these measurements, so be sure to use direct coupling (DC) on the vertical channel you're using.

Use the directions in Exercise 9 to make a pulse measurement on the probe adjustment square wave.

Exercise 9. PULSE WIDTH MEASUREMENTS

To measure the pulse width of the probe adjustment square wave quickly and easily, set your scope to trigger on and display channel 1. Your probe should still be connected to the channel 1 BNC connector and the probe adjustment jack from the previous exercises. Use 0.1 ms/division and the no delay horizontal mode (A sweep if you're using a 2215). Use AUTO triggering on the positive slope and adjust the trigger LEVEL control to get as much of the leading edge as possible on your screen. Switch the coupling on channel 1 to ground and center the baseline on the center horizontal graticule. Now use AC coupling because that will center the signal on the screen and you make pulse width measurements at the 50% point of the waveform. Use your horizontal POSITION control to line up the 50% point with the first major graticule from the left side of the screen. Now you can count divisions and subdivisions across the center horizontal and multiply by the SEC/DIV switch setting to find the pulse width.

Phase Measurements

You know that a waveform has phase, the amount of time that has passed since the cycle began, measured in degrees. There is also a phase relationship between two or more waveforms: the phase shift (if any). There are two ways to measure the phase shift between two waveforms. One is by putting one waveform on each channel of a dual-channel scope and viewing them directly in the chop or alternate vertical mode; trigger on either channel. Adjust the trigger LEVEL control for a stable display and measure the period of the waveforms. Then increase the sweep speed so that you have a display something like the second drawing back in Figure 22. Then measure the horizontal distance between the same points on the two waveforms. The phase shift is the difference in time divided by the period and multiplied by 360 to give you degrees.

Displaying the two waveforms and measuring when one starts with respect to another is possible with any dual trace scope, but that isn't the only way to make a phase measurement. Look at the front panel and you'll see that the vertical channel BNC connectors are labeled X and Y. The last position on the SEC/DIV switch is XY, and when you use it, the scope's time base is bypassed. The channel 1 input signal is still the vertical axis of the scope's display, but now the signal on channel 2 becomes the horizontal axis. In the X-Y mode, you can input one sinusoidal on each channel and your screen will display a Lissajous pattern. (They are named for Jules Antoine Lissajous, a French physicist; say "LEE-za-shu"). The shape of the pattern will indicate the phase difference between the two signal. Some examples of Lissajous patterns are shown in Figure 26.

Note that general purpose oscilloscope Lissajous pattern phase measurements are usually limited by the frequency response of the horizontal amplifier (typically designed with far less bandwidth than vertical channels). Specialized X-Y scopes or monitors will have almost identical vertical and horizontal systems.

X-Y Measurements

Finding the phase shift of two sinusoidal signals with a Lissajous pattern is one example of an X-Y measurement. The X-Y capability can be used for other measurements as well. The Lissajous patterns can also be used to determine the frequency of an unknown signal when you have a known signal on the other channel. This is a very accurate frequency measurement as long as your known signal is accurate and both signals are sine waves. The patterns you can see are illustrated in Figure 26, where the effects of both frequency and phase differences are shown.

Component checking in service or production situations is another X-Y application; it requires only a simple transistor checker like that shown in Figure 27.

There are many other applications for X-Y measurements in television servicing, in engine analysis, and in 2-way radio servicing, for examples. In fact, any time you have physical phenomena that are interdependent and not time-dependent, X-Y measurements are the answer. Aerodynamic lift and drag, motor speed and torque, or

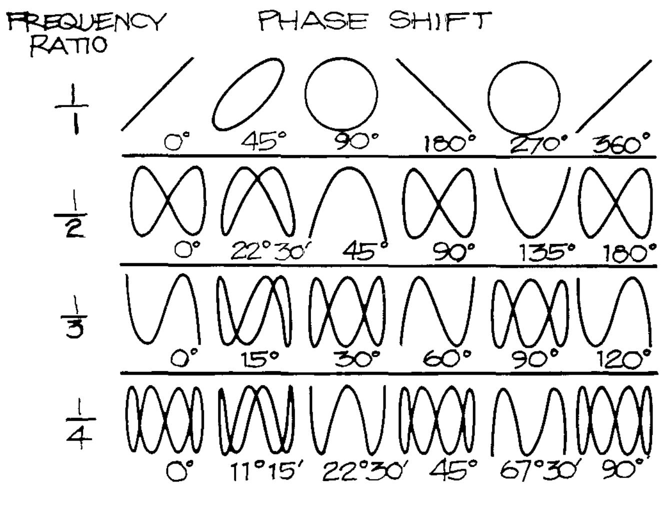


Figure 26.
FREQUENCY MEASUREMENTS WITH LISSAJOUS PATTERNS require a known sine wave on one channel. If there is no phase shift, the ratio between the known and unknown signals will correspond to the ratio of horizontal and vertical lobes of the pattern. When the frequencies are the same, only the shifts in phase will affect the pattern. In the drawings above, both phase and frequency differences are shown.

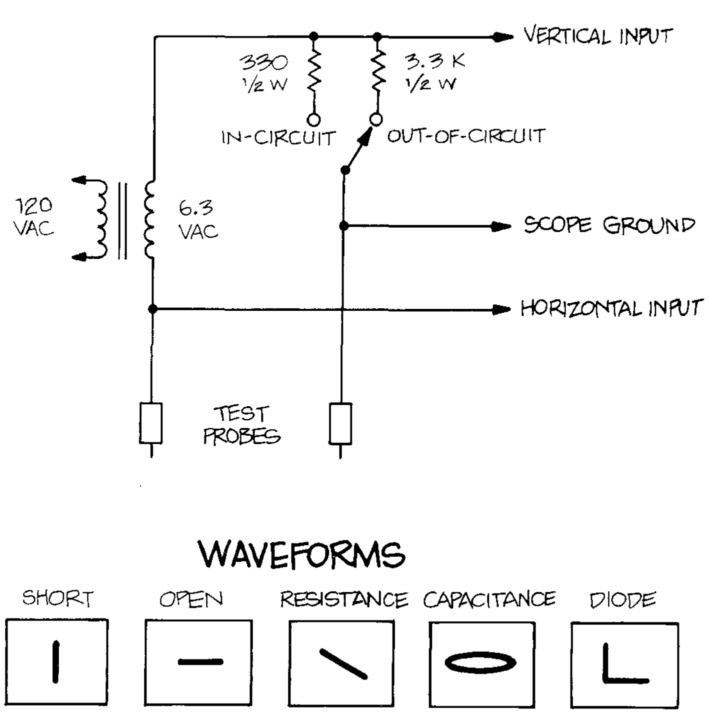


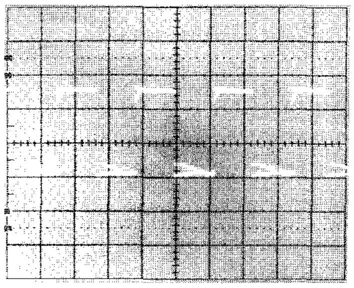
Figure 27.
X-Y COMPONENT CHECKING requires the transistor checker shown above. With it connected to your scope and the scope in the X-Y mode, patterns like those illustrated indicate the component's condition. The waveforms shown are found when the components are not in a circuit; in-circuit component patterns will differ because of resistors and capacitors associated with the component.

pressure and volume of liquids and gasses are more examples. With the proper transducer, you can use your scope to make any of these measurements.

Differential Measurements
The ADD vertical mode and the channel 2 INVERT button of your 2200 Series scope let you make differential measurements. Often differential measurements let you eliminate undesirable components from a signal that you're trying to measure. If you have a signal that's very similar to the unnecessary noise, the set up is simple. Put the signal with the spurious information on channel 1. Connect the signal that is like unwanted components to channel 2. Set both input coupling switches to DC (use AC if the DC components of the signal are too large), and select the alternate vertical mode by moving the VERTICAL MODE switches to BOTH and ALT.

Now set your volts/division switches so that the two signals are about equal in amplitude. Then you can move the right-hand VERTICAL MODE switch to ADD and press the INVERT button so that the common mode signals have opposite polarities.

If you use the channel 2 VOLTS/DIV switch and CAL control for maximum cancellation of the common signal, the signal that remains on-screen will only contain the desired part of the channel 1 input signal. The two common mode signals have cancelled out leaving only the difference between the two.



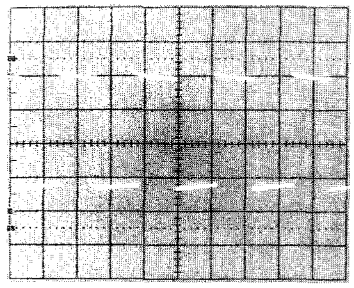


Figure 28.
DIFFERENTIAL MEASUREMENTS allow you to remove unwanted information from a signal anytime you have another signal that closely resembles the unwanted components. For example, the first photo shows a 1 kHz square contaminated by a 60 Hz sine wave. Once the common-mode component (the sine wave) is input to channel 2 and that channel is inverted, the signals can be added with the ADD vertical mode. The result is shown in the second photo.

Using the Z Axis
Remember from Part I that the CRT in your scope has three axes of information: X is the horizontal component of the graph, Y is the vertical, and Z is the brightness or darkness of the electron beam. The 2200 Series scopes all have an external Z-axis input BNC connector on the back of the instrument. This input lets you change the brightness (modulate the intensity) of the signal on the screen with an external signal. The Z-axis input will accept a signal of up to 30 V through a usable frequency range of DC to 5 MHz. Positive voltages decrease the brightness and negative voltages increase it; 5 volts will cause a noticeable change.

The Z-axis input is an advantage to users that have their instruments set up for a long series of tests. One example is the testing of high fidelity equipment illustrated by Figure 29.

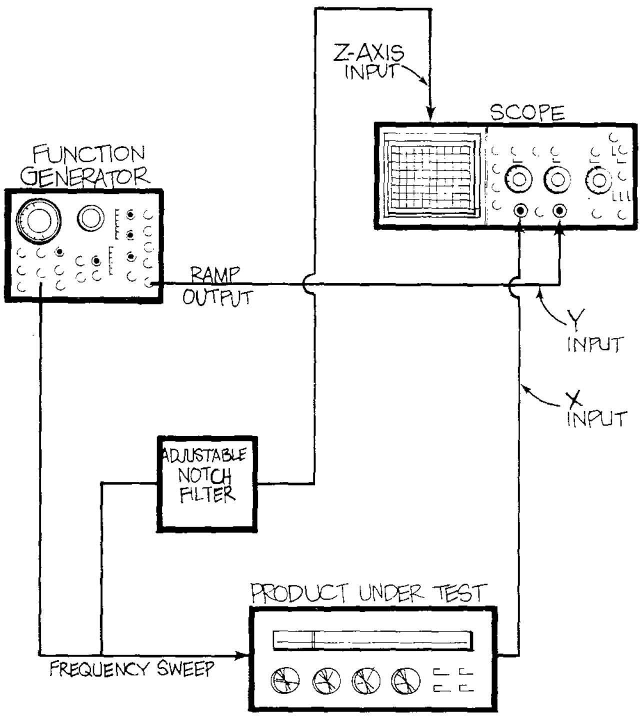


Figure 29.
USING THE Z-AXIS can provide additional information on the scope screen. In the set-up drawn above, a function generator sweeps through the frequencies of interest during the product testing — 20 to 20,000 Hz, in this case. Then an adjustable notch filter is used to generate a marker, at 15 kHz, for instance, and this signal is applied to the Z-axis input to brighten the trace. This allows the tester to evaluate the product's performance with a glance.

Using TV Triggering
The composite video waveform consists of two fields, each of which contains 262 lines. Many scopes offer television triggering to simplify looking at video signals. Usually, however, the scope will only trigger on fields at some sweep speeds and lines at others. The 2200 Series scopes allow you to trigger on either lines or fields at any sweep speed.

To look at tv fields with a 2200 Series scope, use the TV FIELD mode. This mode allows the scope to trigger at the field rate of the composite video signal on either field one or field two. Since the trigger system cannot recognize the difference between field one and field two, it will trigger alternately on the two fields and the display will be confusing if you look at one line at a time.

To prevent this, you add more holdoff time, and there are two ways to do that. You can use the variable holdoff control, or you can simply switch the vertical operating mode to display both channels. That makes the total holdoff time for one channel greater than one field period. Then just position the unused vertical channel off-screen to avoid confusion.

It is also important to select the trigger slope that corresponds to the edge of the waveform where the sync pulses are located. Picking a negative slope for pulses at the bottom of the waveform allows you to see as many sync pulses as possible.

When you want to observe the TV line portion of the composite video signal, use the NORM trigger mode and trigger on the horizontal synchronization pulses for a stable display. It is usually best to select the blanking level of the sync waveform so that the vertical field rate will not cause double triggering.

Delayed Sweep Measurements
Delayed sweep is a technique that adds a precise amount of time between the trigger point and the beginning of a scope sweep. Often delayed sweep is used as a convenient way to make a measurement (the rise time measurement in Exercise 10 is a good example). To make a rise time measurement without delayed sweep, you must trigger on the edge occurring before the desired transition. With delayed sweep, you may choose to trigger anywhere along the displayed waveform and use the delay time control to start the sweep exactly where you want.

Sometimes, however, delayed sweep is the *only* way to make a measurement. Suppose that the part of the waveform you want to measure is so far from the only available trigger point that it will not show on the screen. The problem can be solved with delayed sweep: trigger where you have to, and delay out to where you want the sweep to start.

But the delayed sweep feature you'll probably use the most often is the intensified sweep; it lets you use the delayed sweep as a positionable magnifier. You trigger normally and then use the scope's intensified horizontal mode. Now the signal on the screen will show a brighter zone after the delay time. Run the delay time (and the intensified zone) out to the part of the signal that interests you. Then switch to the delayed mode and increase the sweep speed to magnify the selected waveform portion so that you can examine it in detail.

Since the 2200 Series has two types of delayed sweep, read the paragraphs and use the delayed sweep measurement exercise below that applies to your scope: "Single Time Base Scopes" and Exercise 10 for delayed sweep measurements with single time base scopes like the Tektronix 2213; or "Dual Time Base Scopes" and Exercise 11 for delayed sweep on dual time base scopes like the 2215.

Single Time Base Scopes
Very few single time base scopes offer delayed sweep measurements. Those that do may have measurement capabilities similar to those of the Tektronix 2213 which has three possible horizontal operating modes annotated on the front panel as NO DLY, INTENS, and DLY'D.

When you set the HORIZONTAL MODE switch to NO DLY (no delay), only the normal sweep functions.

When you choose INTENS (intensified sweep), your scope will display the normal sweep and the trace will also be intensified after a delay time. The amount of delay is determined by both the DELAY TIME switch (you can use 0.5 μs, 10 μs, or 0.2 ms) and the DELAY TIME MULTIPLIER control. The multi-

plier lets you pick from 1 to 20 times the switch setting.

The third position, DLY'D (delayed), makes the sweep start after the delay time you've chosen. After selecting this position you can move the SEC/DIV to a faster sweep speed and examine the waveform in greater detail.

This list of horizontal modes should begin to give ideas of how useful these delayed sweep features are. Start by making the rise time measurement described below. (Note that when making rise time measurements, you *must* take the rise time of the measuring instrument into account. Be sure to read Chapter 10.)

Dual Time Base Scopes

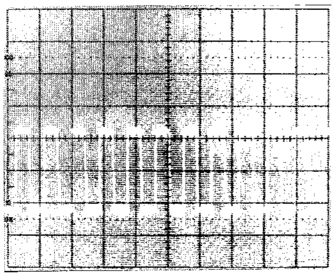
Delayed sweep is normally found on dual time base scopes like the 2215 with two totally separate horizontal sweep generators. In dual time base instruments, one sweep is triggered in the normal fashion and the start of the second sweep is delayed. To keep these two sweeps distinct when describing them, the *delaying sweep* is called the *A sweep;* the *delayed sweep* is called the *B sweep*. The length of time between the start of the A sweep and the start of the B sweep is called the *delay time.*

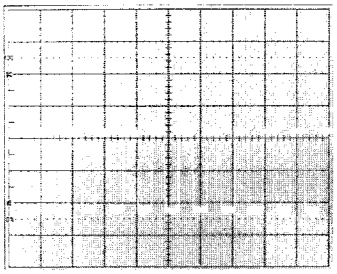
Dual time base scopes offer you all the measurement capabilities of single time base instruments, plus:

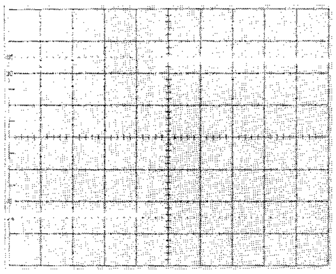
- convenient comparisons of signals at two different sweep speeds
- jitter-free triggering of delayed sweeps
- and timing measurement accuracy of 1.5%.

Most of this increase in measurement performance is available because you can separately control the two sweep speeds and use them in three horizontal operating modes. These modes — in a 2215 — are

Exercise 10. 2213 DELAYED SWEEP MEASUREMENTS







1. *Connect your probe to the channel 1 BNC connector and the probe adjustment jack, hook the ground strap onto the collar of the channel 2 BNC, and make sure the probe is compensated.*

2. *Use these control settings: CH 1 VOLTS/DIV on 0.2 using the 10X probe VOLTS/DIV readout; CH 1 input coupling on AC; VERTICAL MODE is CH 1; TRIGGER MODE is AUTO; TRIGGER SLOPE is negative (−); trigger SOURCE is INT (for internal) and INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is NO DLY; SEC/DIV is 0.5 ms. Check all the variable controls to make sure they're in their calibrated detent positions.*

3. *Set the input coupling to GND and center the trace. Switch back to AC and set the trigger LEVEL control for a stable display. The waveform should look like the first photo above.*

4. *Because a rise time measurement is best made at faster sweep speeds, turn the SEC/DIV control to 2 μs. Use the trigger LEVEL control to try to get all of the positive transition on the screen. You can't; you lose your trigger when you get off the slope of the signal.*

5. *Turn back to 0.5 ms/div and switch to the intensified display with the HORIZONTAL MODE switch. Switch the DELAY TIME to 0.2 ms and use the DELAY TIME MULTIPLIER to move the intensified zone on the waveform to a point before the first complete positive-going transition of the square wave. The intensified zone now shows you where the delayed sweep will start, like the second photo.*

6. *Switch the horizontal mode to DLY'D and the SEC/DIV switch to 5 μs. Now you can use the horizontal POSITION and DELAY TIME MULTIPLIER controls to get a single transition on the screen.*

7. *Change to 0.1 V/div and line up the signal with the 0 and 100% dotted lines of the graticule. (If you have a signal that doesn't fit between the 0 and 100% lines of the graticule, you have to count major and minor divisions and estimate the rise time while ignoring the first and last 10% of the transition.)*

8. *Use the horizontal POSITION control to move the waveform until it crosses a vertical graticule line at the 10% marking. Adjust the FOCUS control for a sharp waveform and make your rise time measurement from that vertical line to where the step crosses the 90% line. Now you can make a rise time measurement on a waveform like that in the third photograph. For example, for 1 major division and 4 minor divisions: 1.8 times the SEC/DIV setting of 5 μs is 9 μs.*

A sweep only, B sweep only, or A intensified by B as well as B delayed. The HORIZONTAL MODE switch controls the operating mode and two SEC/DIV switches — concentrically mounted on a 2215 — control the sweep speeds. See Figure 30.

When you use the ALT (for alternate horizontal mode) position the HORIZONTAL MODE switch, the scope will display the A sweep intensified by the B sweep and the B sweep delayed. As you set faster sweeps with the B SEC/DIV switch, you'll see the intensified zone on the A trace get smaller and the B sweep expanded by the new speed setting. As you move the B DELAY TIME POSITION dial and change where the B sweep starts, you'll see the intensified zone move across the A trace and see the B waveform change.

This sounds more complicated in words than it is in practice. As you use the scope in Exercise 11, you'll find that the procedure is very easy. You will always see exactly where the B sweep starts. And you can use the size of the intensified zone to judge which B sweep speed you need to make the measurement you want.

Measurements at Two Sweep Speeds

Looking at a signal with two different sweep speeds makes complicated timing measurements easy. The A sweep gives you a large slice of time on the signal to examine. The intensified zone will show you where the B sweep is positioned. And the faster B sweep speeds magnify the smaller portions of the signal in great detail. You'll find this capability useful in many measurement applications; see Figure 31 for two illustrations.

Because you can use the scope to show A and B sweeps from both channel 1 and channel 2, you can display four traces. To prevent overlapping traces, most dual time base scopes offer an additional position control. On the 2215, it's labeled ALT SWP SEP for *alternate sweep separation.* With it and the two vertical channel POSITION controls, you can place all four traces on-screen without confusion.

Separate B Trigger

Jitter can prevent an accurate measurement anytime you want to look at a signal that isn't perfectly periodic. But with two time bases and delayed sweep, you can solve the problem with the separate trigger available for the B sweep. You trigger the A sweep normally and move the intensified zone out to the portion of the waveform you want to measure. Then you set the scope up for a triggered B sweep, rather than letting the B sweep simply run after the delay time.

On a 2215, the B TRIGGER LEVEL control does double duty. In its full clockwise position, it selects the run-after-delay mode. At any other position, it functions as a trigger level control for the B trigger. The B TRIGGER SLOPE control lets you pick positive or negative transitions for the B trigger.

With these two controls you can trigger a stable B sweep even when the A sweep has jitter.

Increased Timing Measurement Accuracy

Besides examining signals at two different sweep speeds and seeing a jitter-free B sweep, you get increased timing measurement accuracy with a dual time base scope.

Note that the B DELAY TIME POSITION dial is a measuring indicator as well as a positioning device. The numbers in the window at the top of the dial are calibrated to the major divisions of the scope screen. The numbers around the circumference divide the major division into hundreds.

To make timing measurements accurate to 1.5% with the B DELAY TIME POSITION dial:

- use the B runs-after-delay mode.
- place the intensified zone (or use the B sweep waveform) where the timing measurement begins, and note the B DELAY TIME POSITION dial setting
- dial back to where the measurement ends and note the reading there
- subtract the first reading from the second and multiply by the A sweep SEC/DIV setting.

You'll find an example of this accurate — and easy — timing measurement in Exercise 11.

Figure 30.
THE DELAYED SWEEP CONTROLS of the dual time base 2215 are shown on the photograph above. They include: HORIZONTAL MODE (under the horizontal POSITION control); B TRIGGER SLOPE and LEVEL; ALT SWP SEP (alternate sweep separation, between the two vertical POSITION controls — not shown), and a concentric A and B SEC/DIV control. The B DELAY TIME POSITION dial is at the bottom of the column of horizontal system controls.

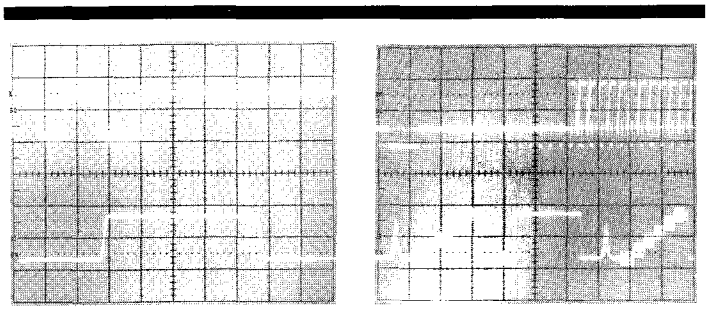
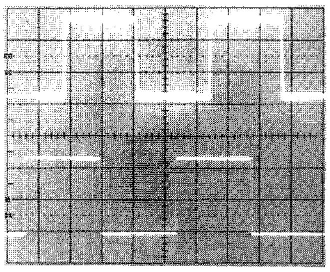
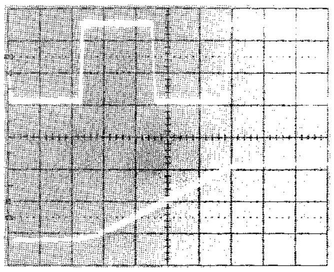


Figure 31.
ALTERNATE DELAYED SWEEP MEASUREMENTS are fast and accurate. One use, examining timing in a digital circuit, is demonstrated in the first photograph. Suppose you need to check the width of one pulse in a pulse train like the one shown. To make sure which pulse you are measuring, you want to look at a large portion of a signal. But to measure the one pulse accurately, you need a faster sweep speed. Looking at both the big picture and a small enlarged portion of the signal is easy with alternate delayed sweep. Another example is shown in the second photo. Here one field of a composite video signal is shown in the first waveform. The intensified portion of that field is the lines magnified by the faster B sweep. With a dual time base scope, you can walk through the field with the B DELAY TIME POSITION dial and look at each line individually.

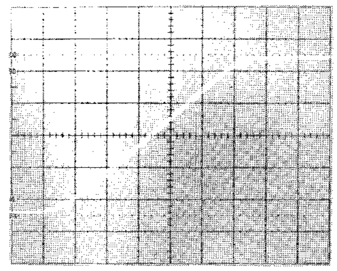
Exercise 11. 2215 DELAYED SWEEP MEASUREMENTS

Rise Time Measurement



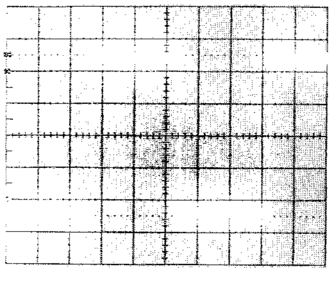


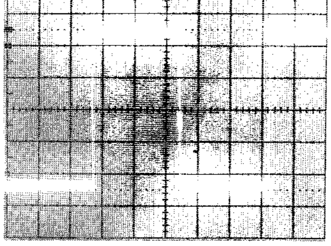
__1.__ Connect your probe to the channel 1 BNC connector and the probe adjustment jack, hook the ground strap onto the collar of the channel 2 BNC, and make sure the probe is compensated.
__2.__ Use these control settings: CH 1 VOLTS/DIV on 0.2 (remember to use the 10X probe readout); CH 1 input coupling on AC; VERTICAL MODE is CH 1; A TRIGGER MODE is NORM; A TRIGGER SLOPE is negative (−); A SOURCE is INT and the A&B INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is A; A and B SEC/DIV is 0.2 ms. Check the variable controls to make sure they're in their calibrated detent positions.
__3.__ Set the A TRIGGER LEVEL control for a stable display and position the waveform in the top half of the screen. Switch to the ALT (for alternate A and B sweeps) display with the HORIZONTAL MODE switch. Use the channel 1 POSITION and ALT SWP SEP (alternate sweep separation) controls to position the two sweeps so that they don't overlap.
__4.__ Use the B DELAY TIME POSITION dial to move the beginning of the intensified zone a point before the first complete positive transition. Your screen should look like the first photo above.
__5.__ Pull out on the SEC/DIV knob and rotate it clockwise to change the B sweep speed to 2 μs/division. This will make the intensified zone smaller; move it to the first rising edge of the waveform as in the second photograph.
__6.__ Switch the horizontal mode to B, the channel 1 vertical sensitivity to 0.1 volts/division, and the sweep speed to 1 μs/division. Use the horizontal and vertical POSITION controls and the B DELAY TIME POSITION control to line up the waveform with the 0 and 100% dotted lines of the graticule. (If you have a signal that doesn't fit between the 0 and 100% lines of the graticule, you have to count major and minor divisions and estimate the rise time while ignoring the first and last 10%.)



__7.__ Position the waveform so that it crosses a vertical graticule line at the 10% marking. Adjust the FOCUS control for a sharp waveform and count major and minor divisions across the screen to where the step crosses the 90% line. If there are 4 major and 8 minor divisions, 4 and 8/10 times the SEC/DIV setting of 1 μs is 4.8 μs. The third photo shows how the screen should look now. (Note: Any jitter you see in the B sweep is from the probe adjustment circuit, not the time base.)
__8.__ One last word on rise time measurements: the accuracy of the measurement you make depends on both the signal you're examining and the performance of your scope. In Chapter 10, you'll find a description of how the scope's own rise time affects your measurement results.

Pulse Width Measurement





__1.__ Use these control settings: CH 1 VOLTS/DIV on 0.1; CH 1 input coupling on AC; VERTICAL MODE is CH 1; A TRIGGER MODE is NORM; A TRIGGER SLOPE is negative (−); A TRIGGER SOURCE is INT (for internal) and INT trigger switch is either CH 1 or VERT MODE; HORIZONTAL MODE is A; A SEC/DIV is 0.2 ms while B SEC/DIV is 0.05 μs. Check the variable controls.
__2.__ Center the first complete pulse of the waveform horizontally. Switch to the ALT display with the HORIZONTAL MODE switch and move the B waveform to the bottom of the screen with the ALT SWP SEP control.
__3.__ Center A sweep waveform vertically. Turn down the intensity so that it's easier to see the small intensified zone.
__4.__ Move the intensified zone to the 50% point of the rising edge of the waveform with the DELAY TIME POSITION control as in the first photo above. Note the delay time reading (the number in the window first, for example: 3.1). Move the intensified zone to the 50% point of the trailing edge as in the second photo and note the reading.
__5.__ The time measurement, a pulse width in this case, is equal to the second dial reading minus the first times the A sweep speed: 5.77 − 3.13 x 0.2 ms = 0.528 ms. In other words, the B DELAY TIME POSITION dial indicates screen divisions for you, 1 complete turn for every major division.

CHAPTER 10. SCOPE PERFORMANCE

There are two aspects to oscilloscope performance: the design parameters of the instrument, and its conformance to those parameters at the time you are making measurements. Making the instrument conform to its design parameters simply means calibration — including making sure the probe is properly compensated as you've done many times already. But even with proper calibration, there will be some effect of the designed performance on your measurements.

Square Wave Response and High Frequency Response

In the design of amplifiers like those in a scope's vertical channels, there is always some compromise between the circuit's high frequency response and its handling of signals with square transitions. Extending the frequency response can be accomplished with high frequency compensation, but too much compensation results in overshoot on a step. Too little extends the measured rise time. The best rise times without overshoot are achieved when the high frequency response is critically damped; the frequency response then falls off smoothly. Figure 32 illustrates the effects of high frequency compensation.

Instrument Rise Time and Measured Rise Times

The rise time of an oscilloscope is a very important specification because the measuring instrument's rise time affects the accuracy of your measured rise times as expressed by this approximation:

$$T_{r\,(measurement)} = \sqrt{T_{r\,(signal)}^{\;2} + T_{r\,(measuring\ system)}^{\;2}}$$

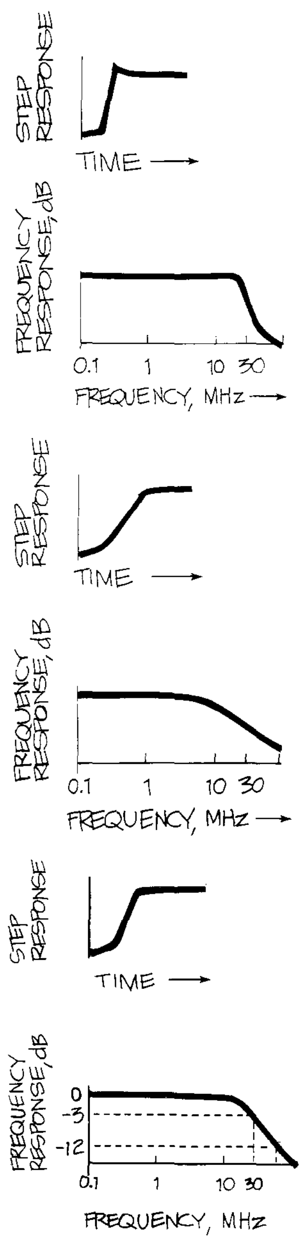


Figure 32.
HIGH FREQUENCY COMPENSATION in a scope's vertical amplifier has an effect on the rise time of square waves measured by the scope. If too much high frequency compensation is present, the rise times will show overshoot and possible ringing, as in the top drawing. Too little, as shown in the second drawing, tends to rolloff the edges of the square wave. A critically damped frequency response is best as in the third drawing.

In practical terms this means that the accuracy of a measured signal will be predictable and will be dependent on how much faster your scope is than the rise time you're measuring. If the measuring scope is five times faster than the observed signal, the measurement error can be as low as 2%. For measurement accuracies of 1%, it takes a scope 7 times faster, as you can see on the chart in Figure 33.

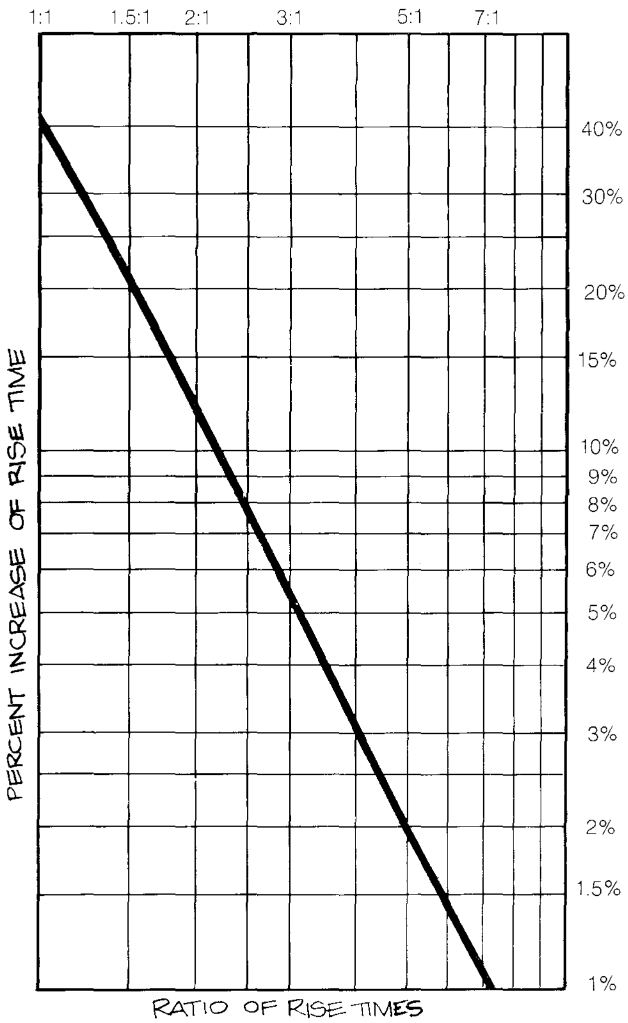
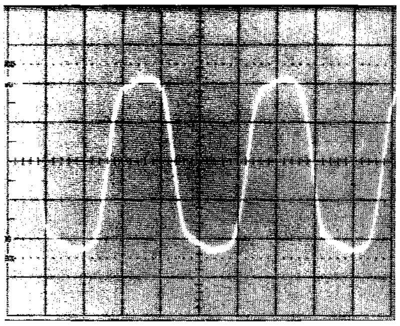


Figure 33.
MEASURED RISE TIME ERRORS depend on the ratio of the measuring system's rise time to the rise time of the signal being measured. As you can see from the chart, when the scope is five times faster the error is a 2% increase in the measured rise time. If the rise times are equal, the error is a 41% increase.

Bandwidth and Rise Time
The vertical channels of an oscilloscope are designed for a broad bandpass, generally from some low frequency (DC) to a much higher frequency. This is the oscilloscope's bandwidth, specified by listing the frequency at which a sinusoidal input signal has been attenuated to 0.707 of the middle frequencies; this is called the −3 dB point. For older instruments, specifications cited both a low and high −3 dB point. Modern instruments, however, have a relatively flat frequency response down to 0 Hz (DC), so only the upper number is quoted as the bandwidth.

A bandwidth specification gives you an idea of instrument's ability to handle high frequency signals within a specified attenuation. But bandwidth specifications are derived from the instrument's ability to display sine waves. A 35 MHz scope will show a 35 MHz sine wave with only −3 dB attenuation, but the effects on a square wave at or near the scope's upper bandwidth limit will be much more severe because high frequency information in the square wave will not be accurately reproduced by the scope. See Figure 34 for an example.



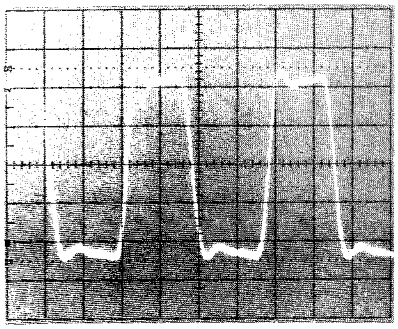


Figure 34.
BANDWIDTH SPECIFICATIONS are based on the scope's ability to reproduce sine waves. The upper bandwidth is the frequency at which a sine wave is reduced to 0.707 of the amplitude shown at middle frequencies. Though this specification tells you how well the instrument reproduces sine waves, not every signal you examine is sinusoidal. Square waves, for example, have a great deal of high frequency information in their rising and falling edges that will be lost as you approach the bandwidth limits of the instrument. To illustrate, the two CRT photos show a 15 MHz square wave reproduced by 35 MHz (top) and 60 MHz (bottom) oscilloscopes.

The frequency response of most scopes is designed so that there is a constant that allows you to relate the bandwidth and rise time of the instrument. This constant is 0.35 and the rise time and bandwidth are related by this approximation:

$$T_r = \frac{0.35}{BW}$$

A simple way to apply the formula is:

$$T_{r\,(\text{nanoseconds})} = \frac{350}{BW_{(\text{megahertz})}}$$

For the Tektronix 2200 Series instruments with a bandwidth of 60 MHz, the rise time is 5.8 nanoseconds.

CONCLUSION
This concludes your introduction to oscilloscopes and the measurements you can make with scopes. You've done well to progress this far, but this primer can only introduce the concepts and measurement techniques. With practice and experience, you'll find yourself making faster and more accurate measurements. Then you too will find that using an oscilloscope is second nature to you.

INDEX

TEK

Tektronix incorporated in 1946 and since then has grown to be the largest manufacturer of oscilloscopes in the world. The list of innovations pioneered by Tek includes: triggered sweeps, calibrated time bases, low-loading probes, bistable and fast-transfer storage. Included in Tek's broad measurement instrument offerings are:

- Portable scopes small enough to hold in your hand or fast enough to measure 350 MHz signals.
- Storage scopes (both analog and digital types) with writing rates as fast as 2500 cm/μs and 14 GHz sampling scopes.
- Modular laboratory scopes as fast as 1 GHz.
- General purpose plug-in instruments like digital counters and multimeters, function generators, distortion analyzers, and programmable calibrators.
- IEEE-488 programmable instruments.
- And accessories to support these instruments including probes, cameras, cables, and scope carts.

Behind all these products is the world-wide Tektronix sales and service organization with 45 offices in the United States and over a hundred in 65 other countries around the world.

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